# USAAVLABS TECHNICAL REPORT 69-44

# SYNCHRONIZATION OF MULTIPOINT HOISTS

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July 1969

## U. S. ARMY AVIATION MATERIEL LABORATORIES
## FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-68-C-0015
SIKORSKY AIRCRAFT
DIVISION OF UNITED AIRCRAFT CORPORATION
STRATFORD, CONNECTICUT

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This report describes the program conducted by Sikorsky Aircraft under the terms of Contract DAAJ02-68-C-0015 to design, fabricate, and test a model electrohydraulic feedback control system for synchronous operation of four hydraulically powered hoists. The object of this contractual effort was to establish the feasibility of the concept and to provide a technique for predicting the performance of future systems.

The feedback control concept for position synchronization of a multipoint hoist system was first introduced by Sikorsky Aircraft under Contract DA 44-177-AMC-467(T), "Design Study of Heavy Lift Helicopter External Load Handling System".

The results of the program under the present contract prove that the electrical feedback control concept is technically feasible and that a reasonable prediction of performance for similar future systems may be attained by analytical methods.

The conclusions contained herein are concurred in by this Command. It is believed that the hoist control system concept is sufficiently developed for transition to a full-scale demonstrator system.

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# SYNCHRONIZATION OF MULTIPOINT HOISTS

Final Report

Sikorsky Engineering Report 50583

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## ABSTRACT

Sikorsky Aircraft has conceived an electrohydraulic feedback system that will provide position synchronization of four aircraft cargo hoists. To demonstrate the feasibility of the concept and to verify the method of analysis, Sikorsky Aircraft has designed, fabricated, and tested a model four-point synchronized hoist system. Test results show that the feedback system concept provides adequate synchronization control; i.e., the platform pitch and roll angles do not exceed $\pm 5^{\circ}$. The analysis derived to predict performance of the feedback system was shown to be valid.

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## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | cable metallic area, in.$^2$ |
| $A_A$ | port area restricting aft flow, in.$^2$ |
| $A_F$ | port area restricting forward flow, in.$^2$ |
| $A_1$* | port area restricting flow to winch #1, in.$^2$ |
| $cg_x$ | x-location of load center of gravity, ft |
| $cg_y$ | y-location of load center of gravity, ft |
| CIPR | cubic inches per revolution, in.$^3$/rev |
| cps | cycles per second |
| $e$ | elastic stretch, ft |
| $e_{output}$ | potentiometer output voltage, v |
| $E$ | modulus of elasticity, psi |
| $G_{FA}$ | gain on difference in lengths of cables (1 & 4), ma/ft |
| $G_{ps}$ | gain on difference in lengths of cables (1 & 2) and (3 & 4), ma/ft |
| $LOAD_{max}$ | maximum load overall, lb |
| $l$ | length of cable, ft |
| $L_1$* | length of cable #1, ft |
| ma | milliampere |
| $P_A$ | pressure at aft flow divider, psi |
| $P_F$ | pressure at forward flow divider, psi |
| $P_S$ | demanded supply pressure, psi |
| $P_{Smax}$ | maximum supply pressure, psi |
| $P_1$* | pressure at winch #1, psi |

| | |
|---|---|
| $Q_A$ | flow to aft flow divider gpm |
| $Q_C$ | flow to master flow divider, gpm |
| $Q_F$ | flow to forward flow divider, gpm |
| $Q_1$* | flow to winch #1, in.$^2$ |
| $Q_{max}$ | rated flow for hydraulic pump, gpm |
| RATE | commanded winch rate, ft/min |
| $RATE_{max}$ | rated winch rate, ft/min |
| $R_\Omega$ | total potentiometer resistance, ohms |
| $T_1$* | tension in cable #1, lb |
| X | X-axis of platform (forward) |
| $V_{input}$ | potentiometer input voltage |
| wt | weight of load, lb |
| Y | Y-axis of platform (starboard) |
| $\Delta$cable | cable stretch, in. |
| $\delta$(i) | Kroniger delta, a mathematical artifice, having the value of 1 or 0, that indicates whether or not winch (i) is in stall in the analysis |
| $\theta$p | angle platform makes with respect to the X-axis of airframe, deg |
| $\phi$p | angle platform makes with respect to the Y-axis of airframe, deg |

*Similar definitions apply for the other three corners (e.g., $A_2$, $Q_2$, etc.)

# INTRODUCTION

## BACKGROUND

Multiple-point suspension systems used for carrying external helicopter loads offer several advantages when compared with single-point suspension systems. Among the advantages are higher aircraft speed due to increased load stability, ease in securing large nonsymmetrical loads, and load maneuverability. Sikorsky Aircraft has designed and tested a four-point hoist system as part of the cargo handling system of the CH-54A aircraft. This system utilizes conventional flow divider-combiners to proportion flow and thereby synchronizes hoisting rates. The CH-54A four-point hoist system has demonstrated sensitivity to load symmetry, particularly in the lifting mode. Because of the open-loop type of control, the synchronization errors are cumulative and are directly proportional to cable travel.

As part of the external cargo handling study conducted for the U.S. Army Aviation Materiel Laboratories under Contract DA 44-177-AMC-467(T), Sikorsky Aircraft recommended a feedback control system for synchronizing four hydraulically powered hoists. Sikorsky Aircraft proposed testing of the feedback control system by utilizing a model system.

This report describes the program conducted by Sikorsky Aircraft to evaluate a model electrohydraulic feedback control system for synchronous operation of four hydraulically powered hoists under Contract DAAJ02-68-C-0015.

## OBJECTIVES OF PROGRAM

The objectives of this program are twofold:

- To evaluate the adequacy of the electrohydraulic feedback system to synchronize the operation of multiple hoists for helicopter operations.

- To develop and evaluate the analytical techniques necessary to predict the performance of this type of system.

These objectives have been achieved by designing, fabricating, and testing a model system that simulates the performance of the full-scale system and that provides experimental verification of the analysis.

## CONCEPT

The basic concept is classical in nature. The lengths of the cables are continually sensed. The sensing signals are compared and summed, and a differential signal is directed to an electrohydraulic control valve. The valve responds to the error signal to modify the speeds of the individual hoists to reduce the error.

## SYSTEM DESIGN

### SYSTEM OPERATION

The model hoist system designed for this program is comprised of four hydraulically powered hoists which can be controlled electrically by an operator on the ground. Two modes of operation can be selected by the operator:

> Collective operation, wherein all four hoists can be operated simultaneously in the same direction.
>
> Beeping operation, wherein any one hoist can be operated individually.

Both modes of operation at individual hoist loads to 200 lb at rated speed are possible. The two modes cannot be performed simultaneously, nor can two hoists be beeped simultaneously. This characteristic is not inherent in the feedback circuit but is the result of the simplified circuit designed solely to evaluate the concept of feedback control of four hoists.

### HYDRAULIC SYSTEM DESIGN

Basically, the design of a multiple-function hydraulic system supplied by a common power source is one wherein the flow rates to the individual subfunctions are determined by pressure demand. System operation is directly analogous to that of a parallel electrical circuit in which current (flow) seeks the path of least resistance, and the currents (flow rates) are inversely related to the resistance (loads) in each path. In a hoisting system where the loads at the four points are not normally equal, an unsynchronized system would result in unequal cable excursions, thus warping or even upsetting the loads.

Equalization of flow in this type of hydraulic circuit is achieved by selecting the path of greatest impedance and adding restriction to the remaining paths so that the impedances in all paths are equivalent. In this application, impedance is assumed to be the total resistance to fluid flow due to loads, line losses, and restrictors in the system. Several methods of equalizing impedance in hydraulic systems are available through the use of off-the-shelf components. One such system employs flow divider-combiner valves which attempt, in the divider mode, to divide flow from a single input path into two equal output paths or, in the combiner mode, to equalize two input flows and to combine them into a single output flow. While this system equalizes the flow rates within the tolerance of the valves, other factors such as the efficiency of the motors and erratic hoist behavior introduce additional errors which are outside the error-sensing

loop of the valves. Cumulatively, these errors can become significant. The system designed for this study employs an electrical feedback loop, wherein system output (i.e., individual drum revolutions) is sensed and corrections are made in order to accommodate these errors.

The model system employs three flow divider-combiner valves. The valves respond to restrict flow in either of the two paths in proportion to the magnitude and polarity of an electrical signal. The electrical signal is the output from a summing amplifier circuit which receives inputs from two potentiometers. The flow-divider valves were developed for Sikorsky Aircraft for use on the CH-53A model helicopter.

Signals for the valves are derived from potentiometers that are mounted on each hoist to sense drum position, which is directly related to the length of cable payed out. By directing the signals from a set of two hoists to the amplifier circuit that controls one flow-divider valve, the proper relationship between drum positions in a set of hoists can be maintained. An additional amplifier circuit is used to provide a signal to a separate flow-divider valve. A signal from a hoist in one set is compared to that from a hoist in another set; this signal is used to proportion flow between the two sets of hoists. In this manner, synchronization between the two sets of hoists is achieved.

Figures 1 and 2 illustrate the hydraulic and electrical circuit diagrams.

## ELECTRICAL CIRCUIT

The circuit selected was based on the original four-point synchronized circuit suggested in the external cargo handling study, heavy lift helicopter, Contract DA 44-177-AMC-467(T)[1].

A variety of operational characteristics result from the technique used to measure differential cable length. Among these are steady-state and dynamic accuracy adjustment capability, and several damping and frequency settings. The potentiometers are grounded directly, leaving the wiper to sense the potential exactly proportional to cable length. A direct ground of potentiometers eliminates any errors due to differences in total potentiometer resistance; only the negligible errors concerned with linearity and resolution remain. The wipers are connected to differential operational amplifiers. These devices amplify the differential voltage between appropriate wipers with virtually no load on the potentiometers, minimizing the effect of potentiometer linearity.

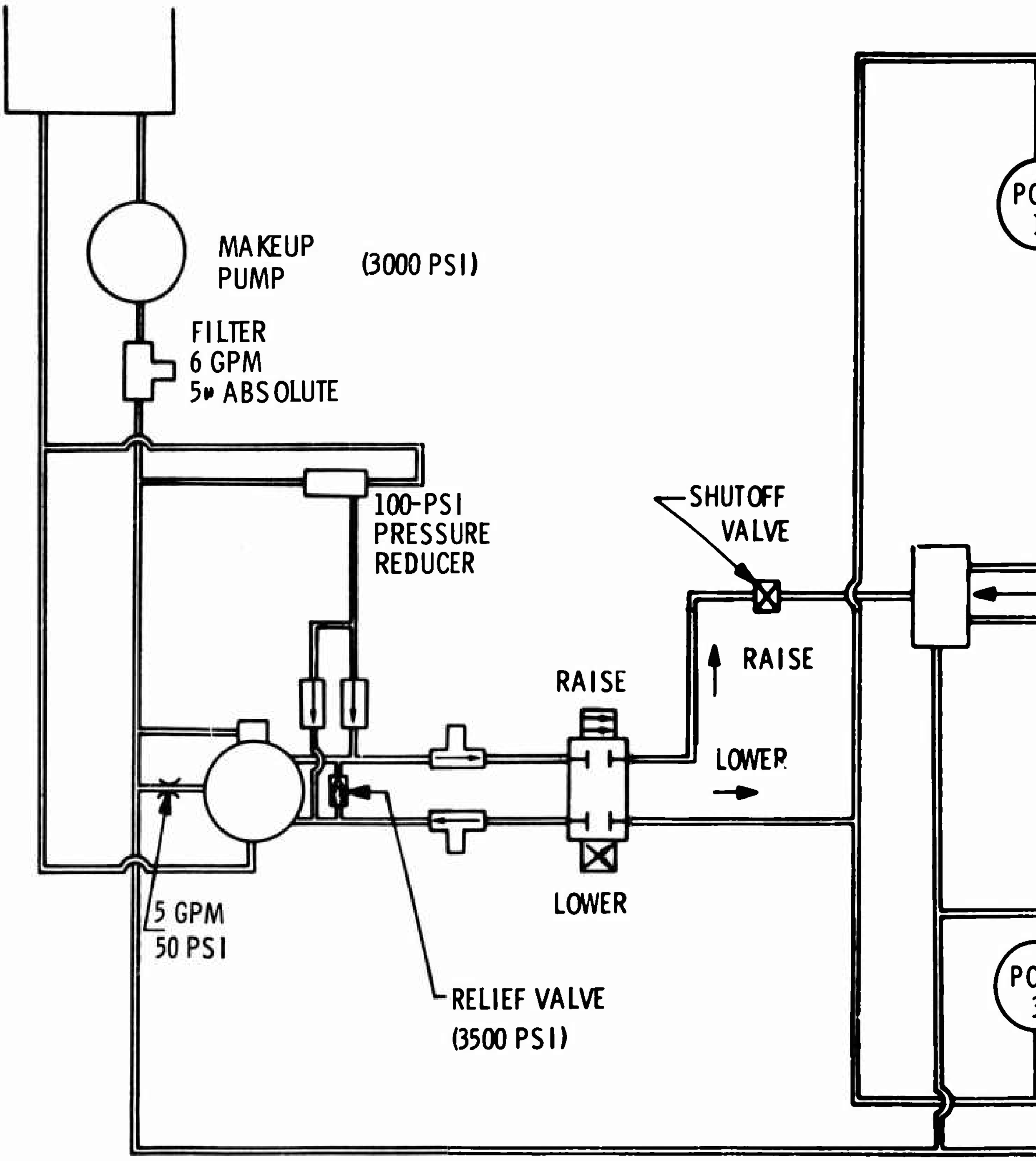
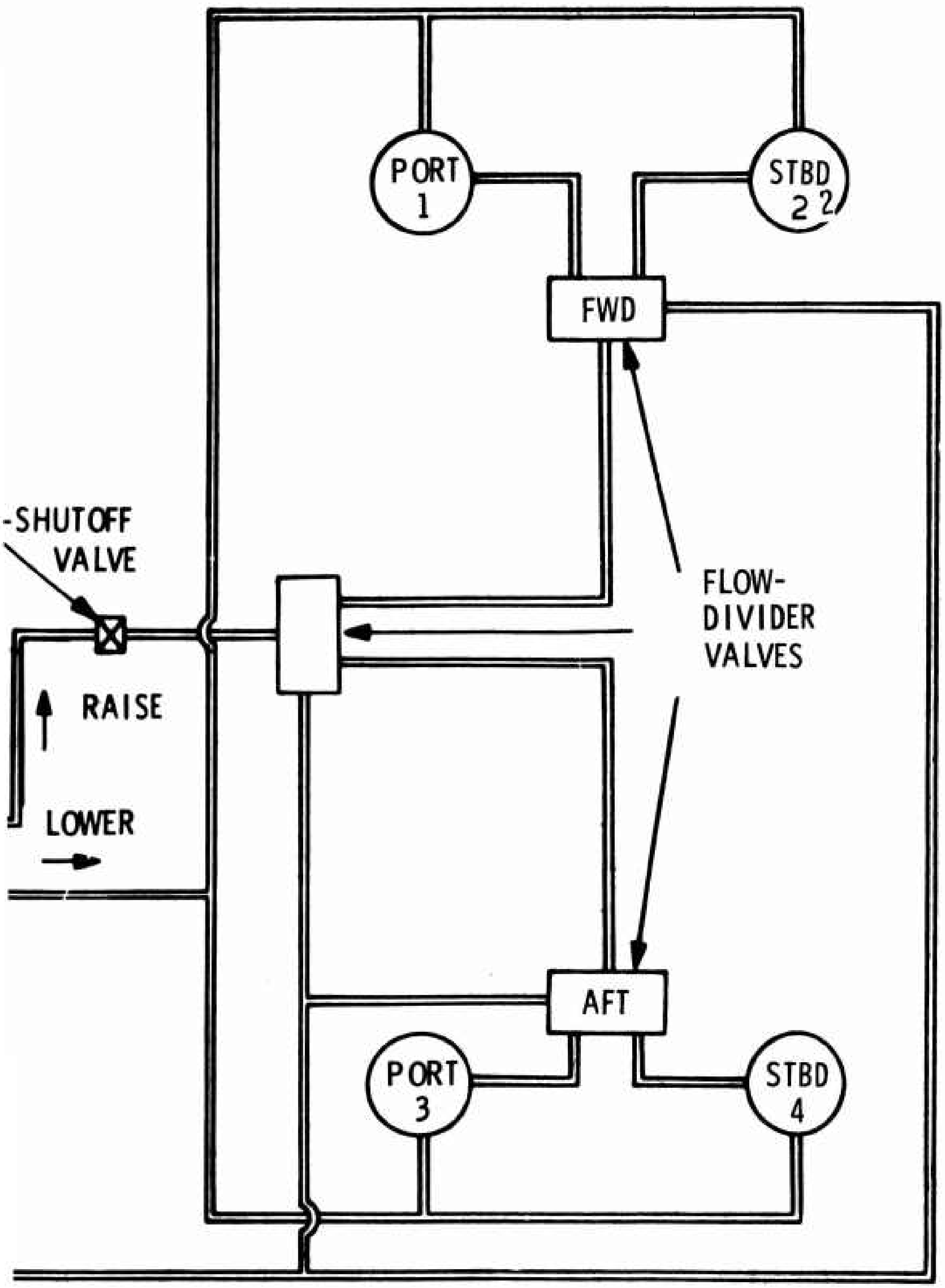



Figure 1. Hydraulic Circuit.



PORT
1
STBD
2 2
FWD
-SHUTOFF
VALVE
FLOW-
DIVIDER
VALVES
RAISE
LOWER
AFT
PORT
3
STBD
4


B

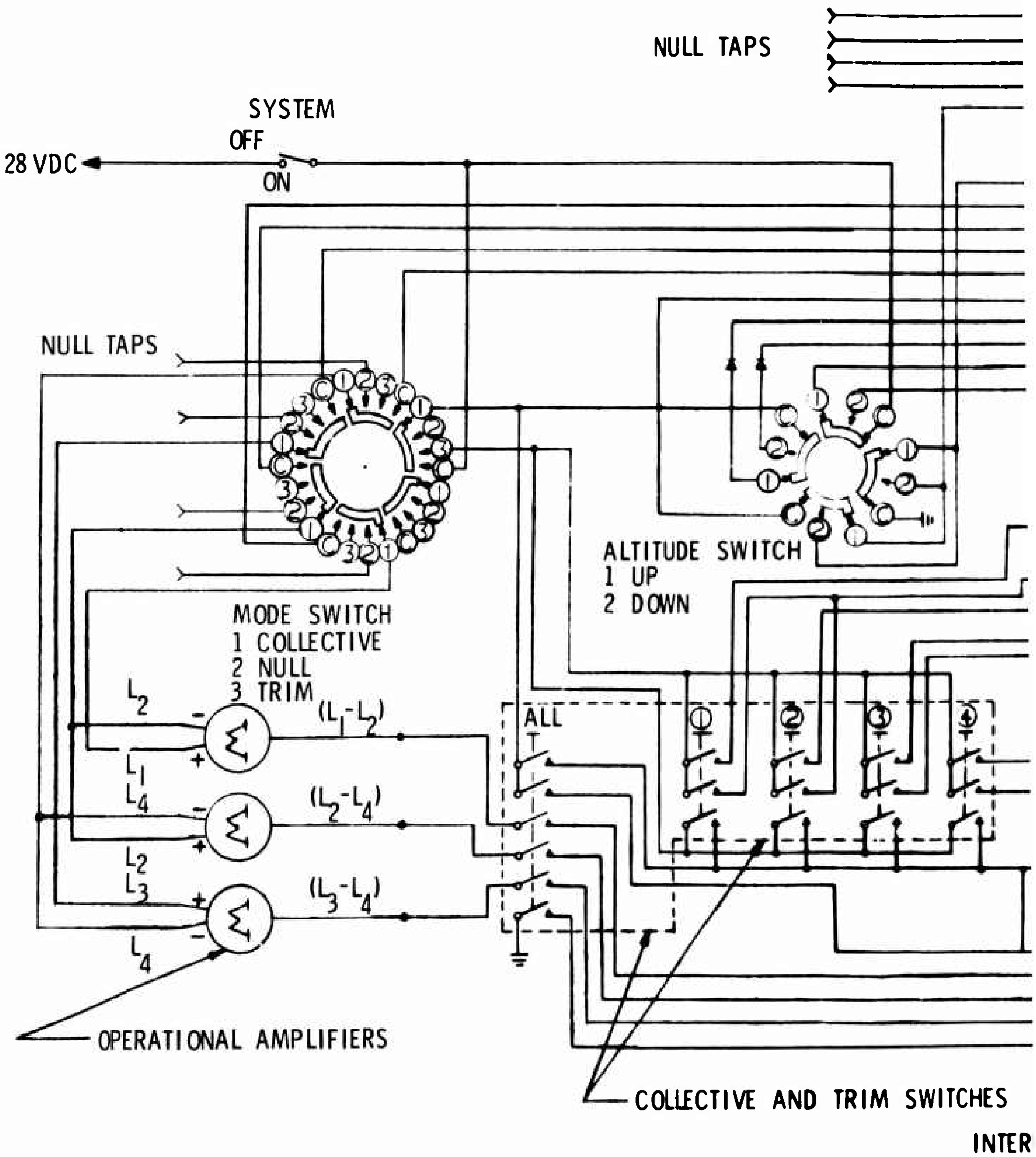
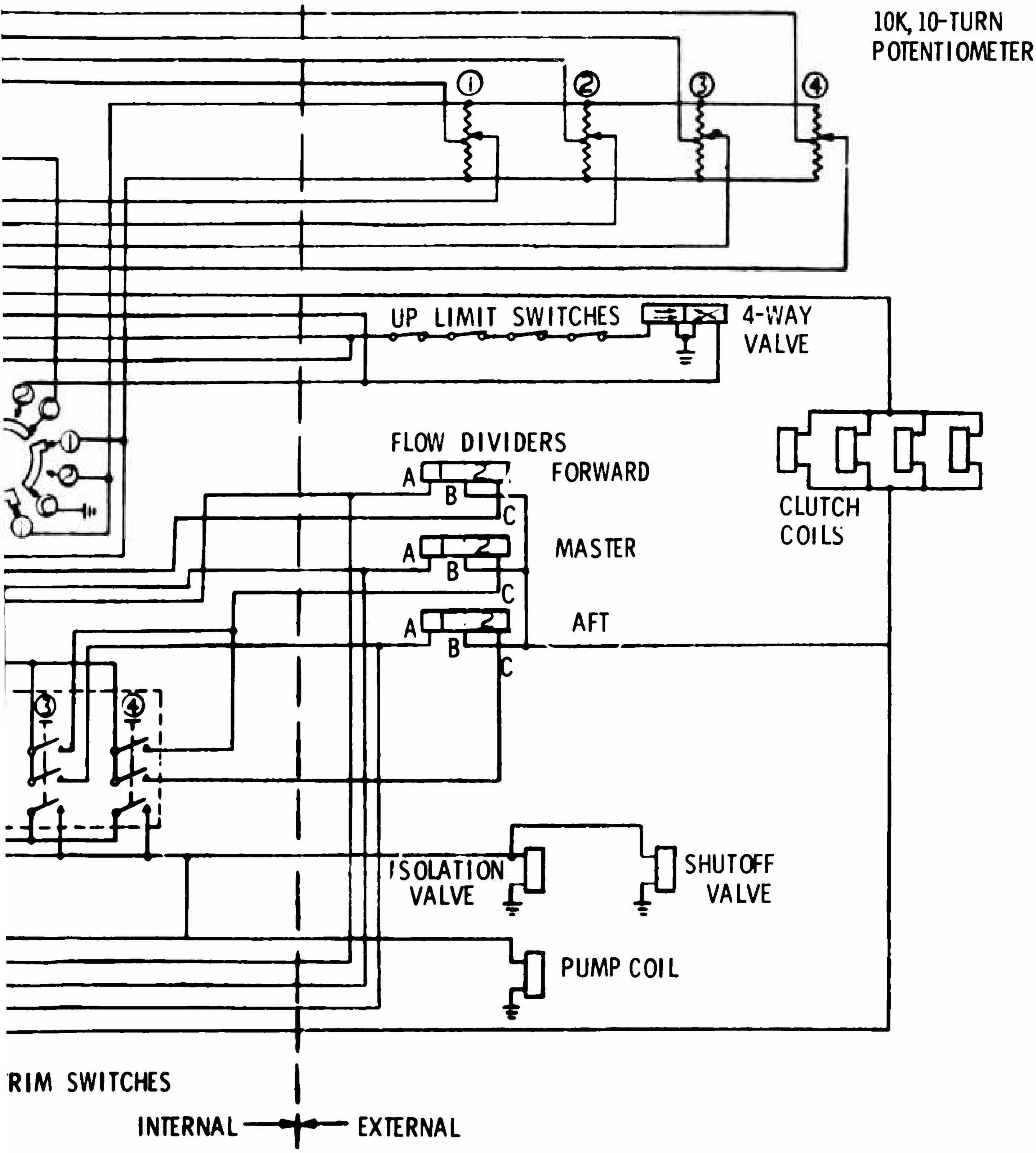



Figure 2. Electrical Circuit.



10K, 10-TURN POTENTIOMETER
UP LIMIT SWITCHES
4-WAY VALVE
FLOW DIVIDERS
FORWARD
MASTER
AFT
A
B
C
CLUTCH COILS
ISOLATION VALVE
SHUTOFF VALVE
PUMP COIL
RIM SWITCHES
INTERNAL
EXTERNAL

## MAJOR COMPONENTS

### Hoists

The hoists used in this system are modified rescue hoists. The hoist is driven by a hydraulic motor; the motor drives through a two-stage planetary gearing system which reduces speed and increases torque. The hoist is a single-wrap, drum-type, level-wind configuration. The hoist contains a Weston[2] disc-type load brake which will hold the cable if there is a hydraulic failure and which controls the rate of pay-out. Cable speed of the hoist is 100 fpm.

### Hydraulic Motors

The rescue hoist used in this test was originally equipped with a motor of 0.6-CIPR (cubic inches per revolution) displacement, which requires 1000-psi hydraulic pressure to react at full load. For this program, higher operating pressures were desirable in order to include the effect of hydraulic fluid compressibility in the tests. A 0.25-CIPR motor that will deliver rated torque in a 3000-psi system was selected; this is considered to be adequate since the bulk modulus of hydraulic fluid is essentially constant above 2000 psi. Because of weight considerations, it is anticipated that any operational aircraft system will utilize system pressures above this range. Photographs of the hoist are shown in Figures 3 and 4.

### Flow-Divider Valves

The selection of flow-divider valves was determined entirely by availability. While the valves selected do not exhibit the linear flow vs. electrical characteristics which would be most easily incorporated into a computer program, the characteristics of the selected valves can be accommodated, and performance has been predicted. A photograph of the flow dividers as mounted on the hoisting platform is shown in Figure 5. The flow-divider characteristic is shown in Figure 6. A schematic of the flow divider is shown in Figure 7.

### Power System

The power system used for the four-point synchronized hoist is similar to the power system used for the four-point hoist test.[3]

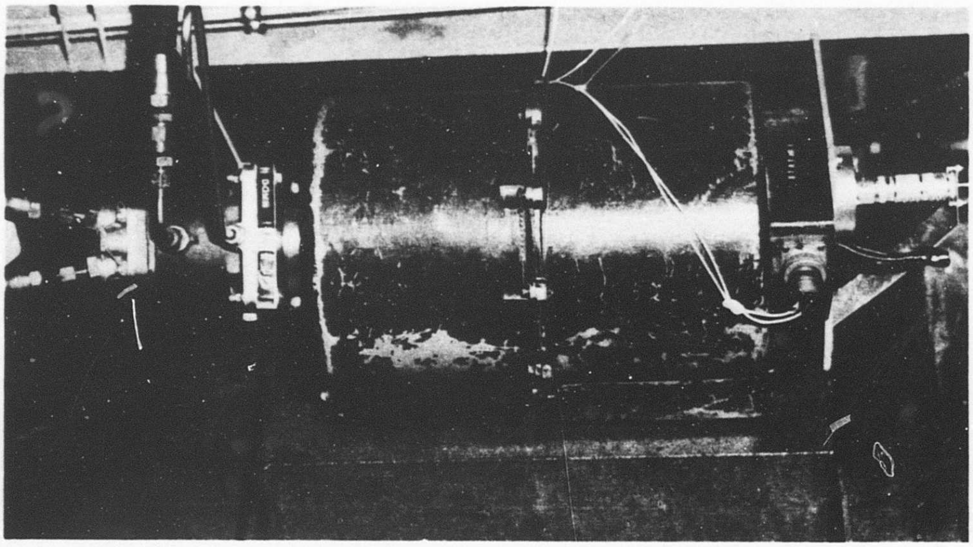


Figure 3. Modified Rescue Hoist, Mounted.

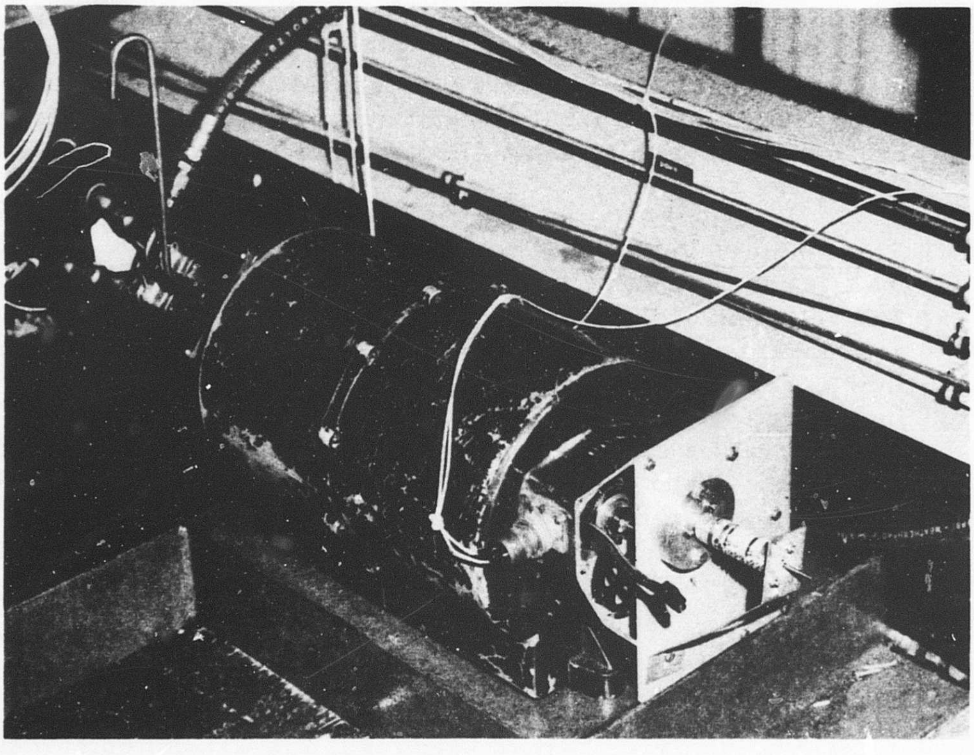


Figure 4. Potentiometer End, Modified Rescue Hoist.

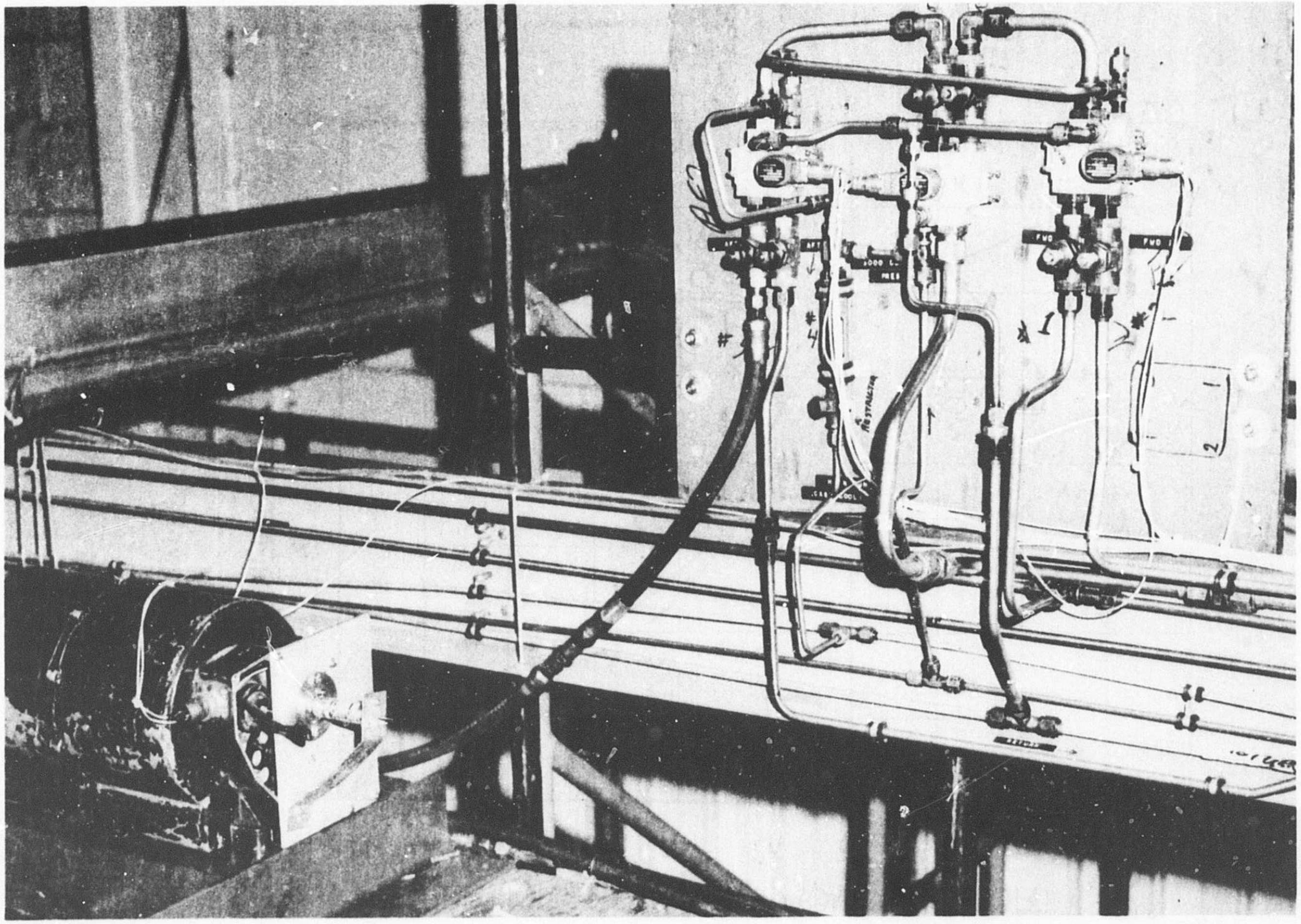


Figure 5. Flow-Divider Valves, Hoist Platform.

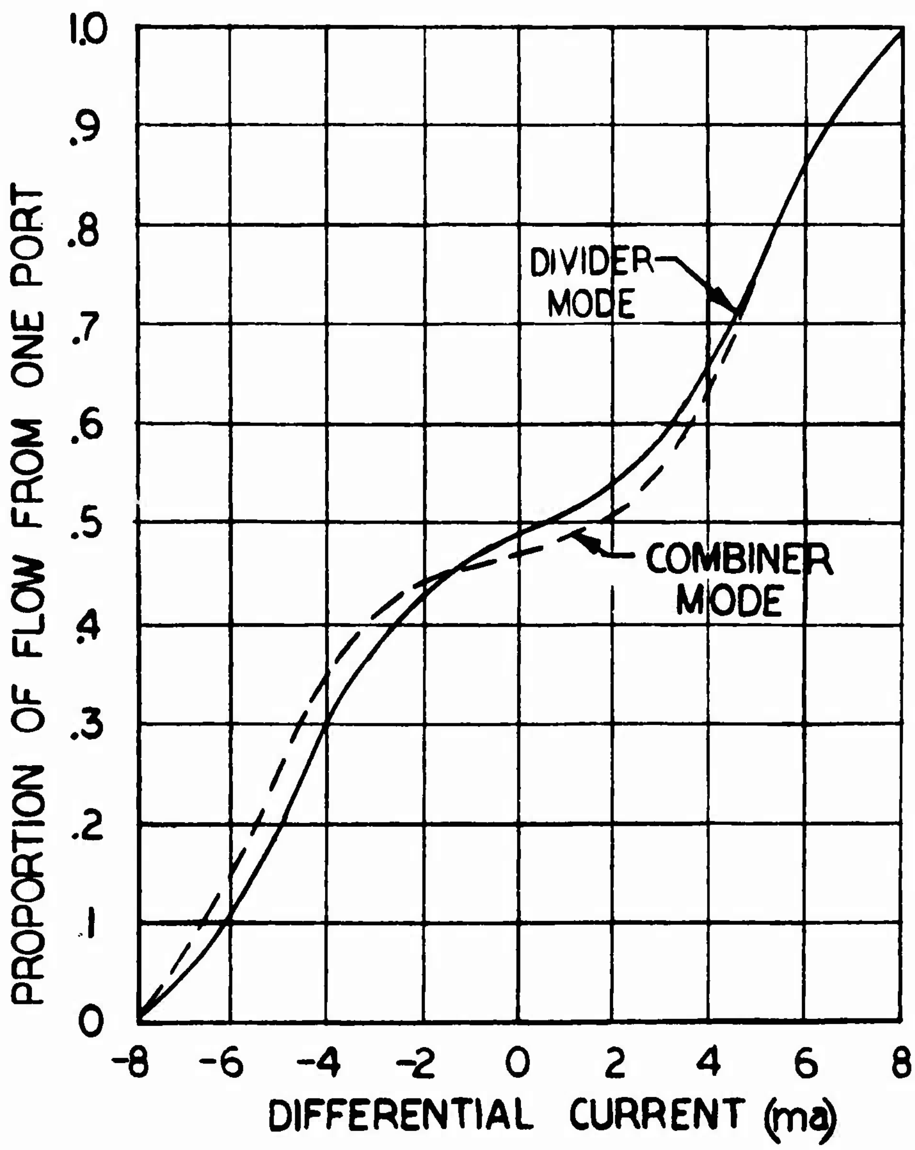



Figure 6. Flow-Divider Characteristic.

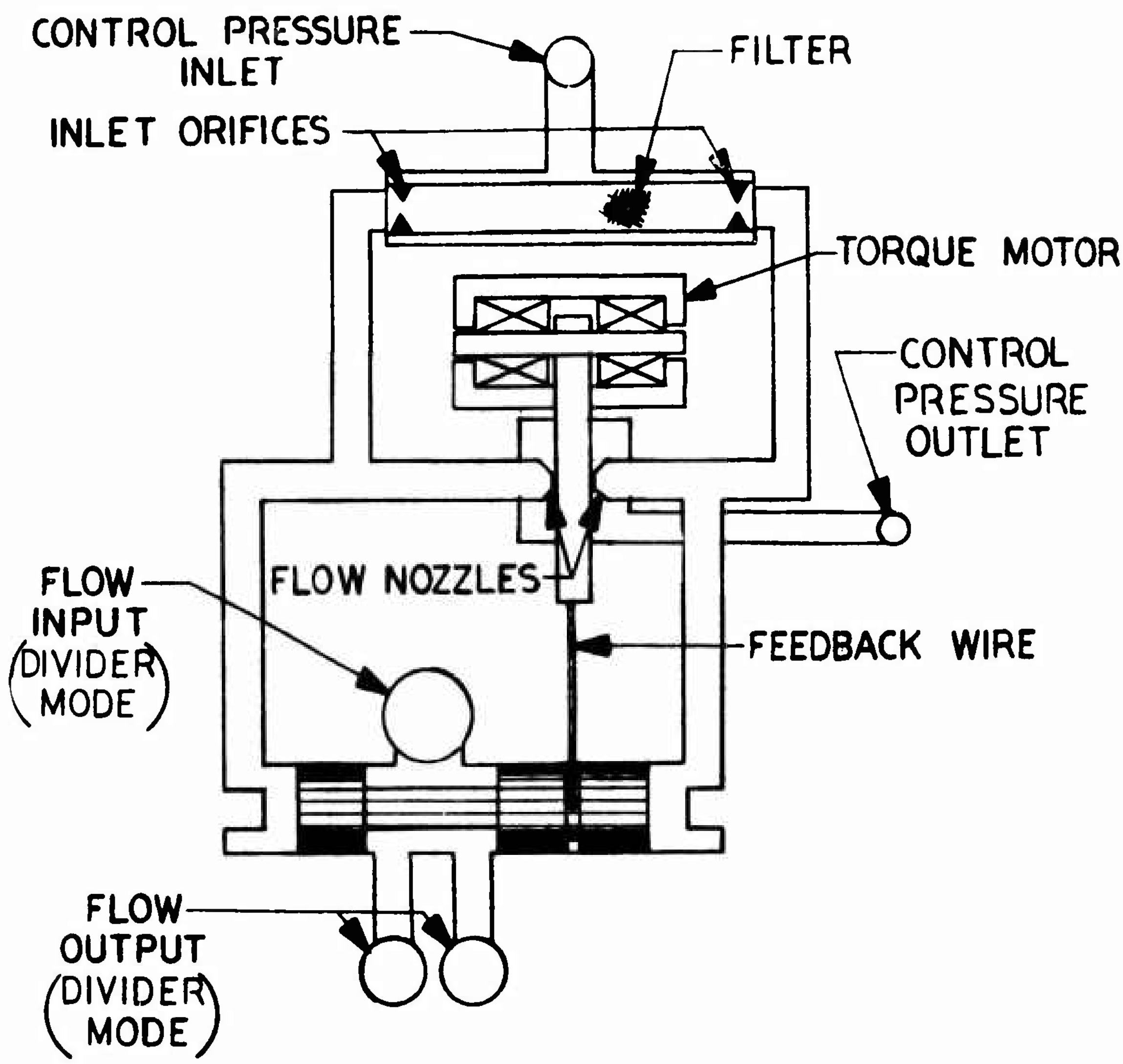



Figure 7. Flow-Divider Schematic.

The hoist system utilizes a closed pressure demand system; pressure is established by load on the system. Flow rate is established by a servo control on the pump. The hoist hydraulic system has no reservoir, and return flow passes directly into the pump inlet. Pump inlet pressure and replenishment of leakage losses are supplied by a makeup system. The makeup system is provided with a separate pump. Cooling flow for the servo-controlled pump and control pressure for the pump servo control and the system flow-divider valves are provided by the makeup system.

## Valves

The valves for this test have the same requirements (reverse-direction capability and capability of opening and closing with pressure applied in either direction) as those used on the four-point hoist test;[3] therefore, similar valves were selected.

## Operational Amplifiers

Operational amplifiers draw virtually no current from the potentiometers; hence, the need for trimming potentiometers mounted on the hoists to compensate for nonlinearities is eliminated. A transistor booster circuit enables the amplifier circuit to put out 50 ma with virtually no distortion. The amplifiers are precisely linear up to ± 10 volts.

## Potentiometers

Accuracy was the harshest constraint on the choice of the potentiometers. In the circuit designed for the four-point system, operational amplifiers are used to boost the outputs of the potentiometers; hence, no output loading is incurred. Thus, errors due to potentiometer nonlinearity are minimized, and ± .5% linearity is sufficient. A 10-turn potentiometer was chosen to give adequate resolution. A solenoid clutch allows the potentiometers to be disengaged except during collective operation, providing the control system with memory during trim adjustments. The clutch slip threshold provides protection against running the potentiometers past their stops.

## Control Systems

The system controls are housed in an aluminum chassis, which may be mounted at a control station or attached to a 30-ft extension cord for walk-around operation. Gain-setting potentiometers

contained inside the chassis may be adjusted for optimum system performance. Pushbutton operation was desirable from the human factors viewpoint. A lockout feature on the multiswitch allows the substitution of rotary switches for relays to obtain the switching logic. The operator cannot command two functions at once, precluding command signals which could damage components in the system. A photograph of the control chassis is shown in Figure 8.

## Mechanical

### Hoist Drive

An adapter shaft and housing were designed and fabricated to mount the hydraulic motor to drive the hoist. Figure 9 illustrates the hoist drive system.

### Potentiometer Drive

A potentiometer drive providing variable resistance proportional to the length of cable payed out was designed. The potentiometer is mounted on a housing which also serves as the potentiometer drive shaft support bearing housing. The potentiometer drive shaft is driven by single-stage antibacklash spur gearing adapted to an existing shaft on the hoist drum and is mated to the potentiometer by a flexible coupling. Figure 10 illustrates the potentiometer drive.

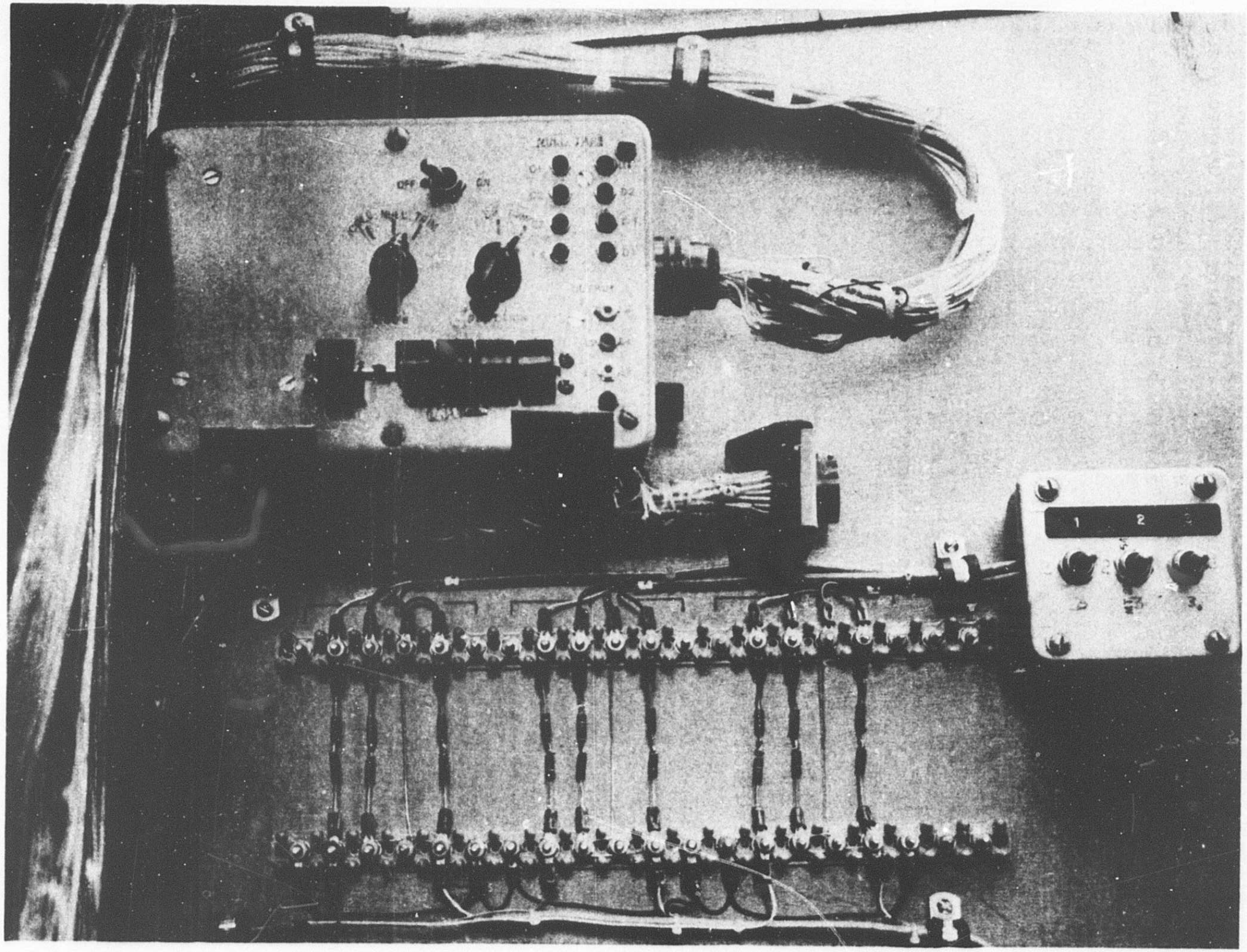


Figure 8.  Control Chassis.

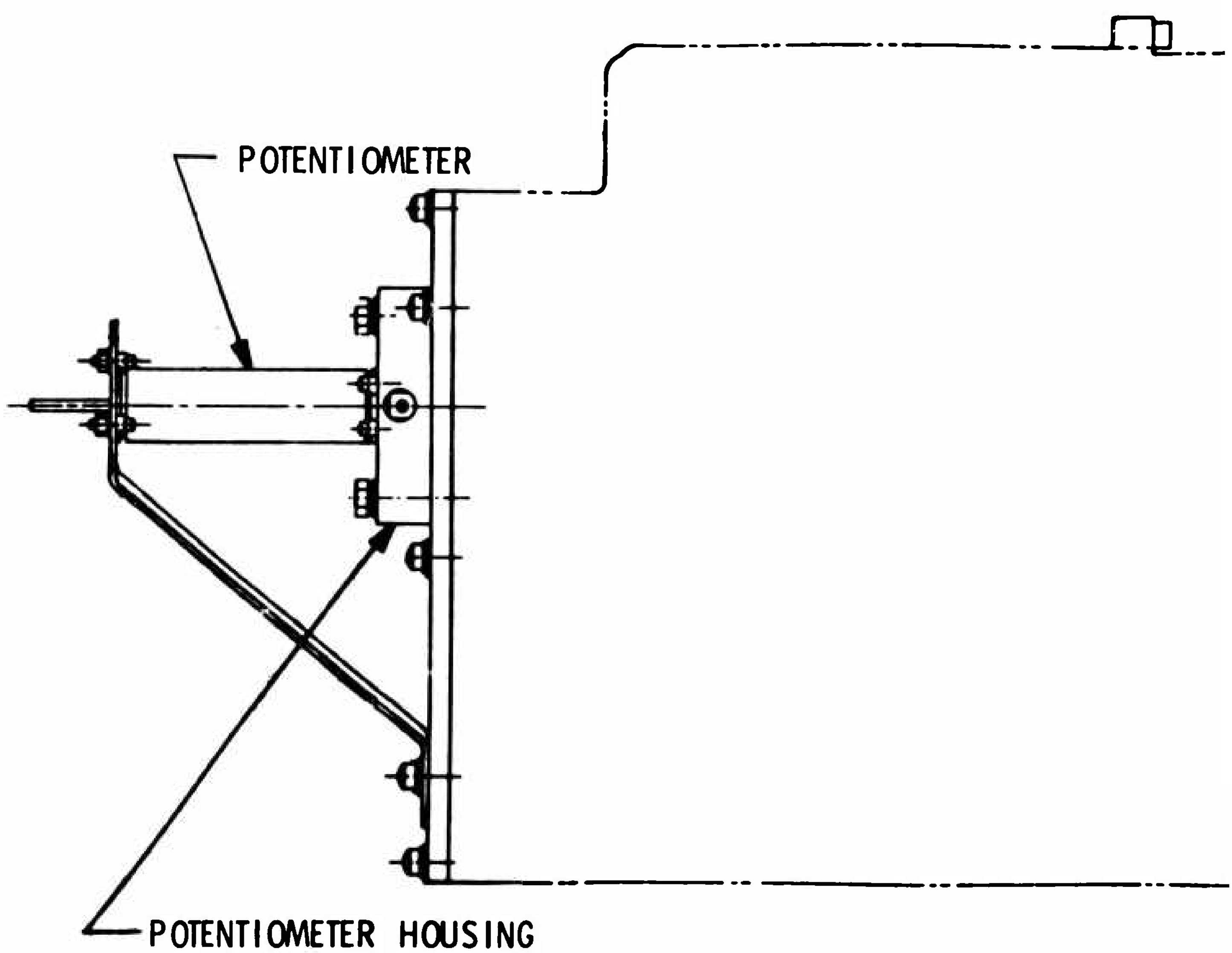
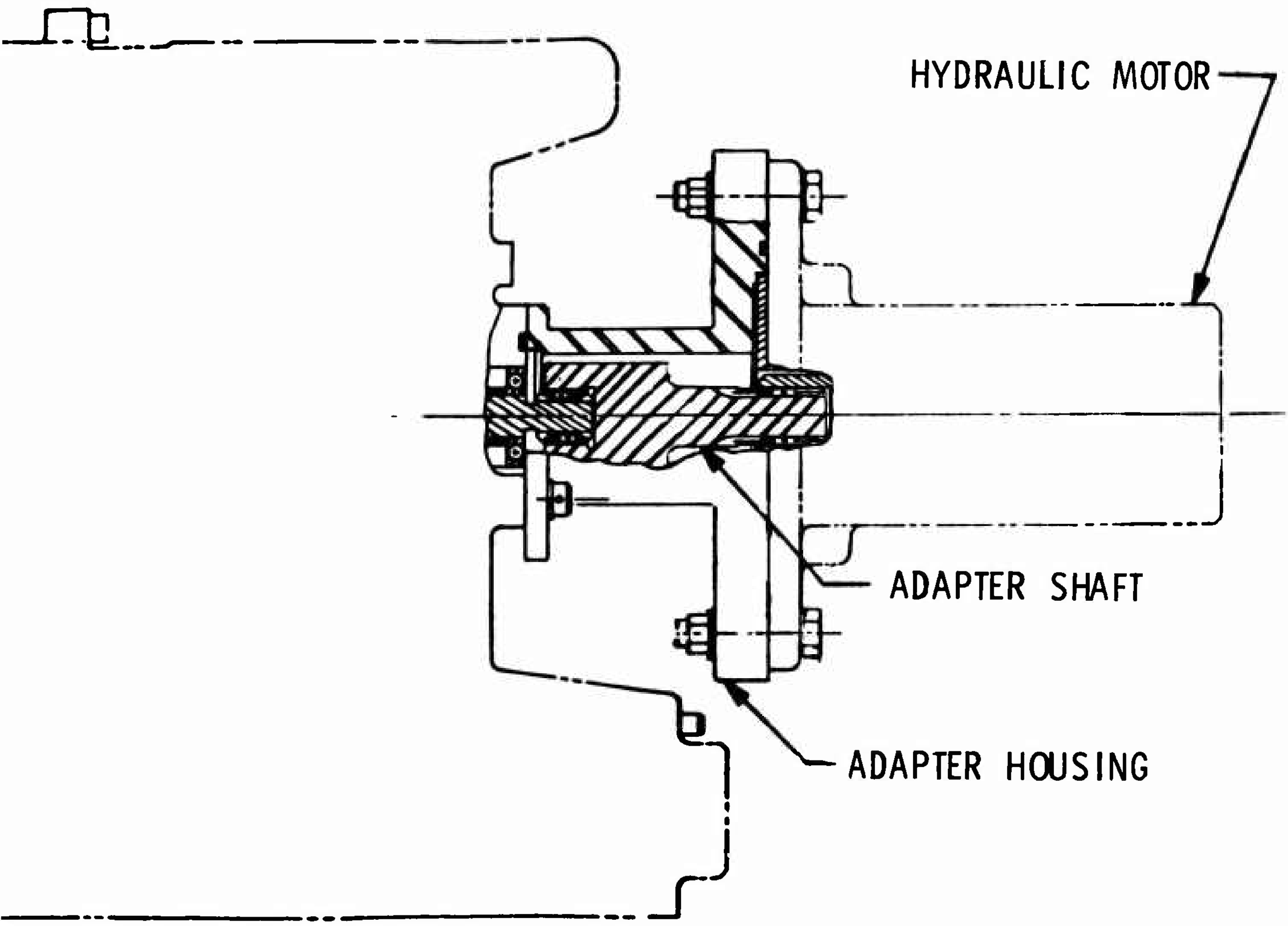



Figure 9. Modified Rescue Hoist.


HYDRAULIC MOTOR
ADAPTER SHAFT
ADAPTER HOUSING

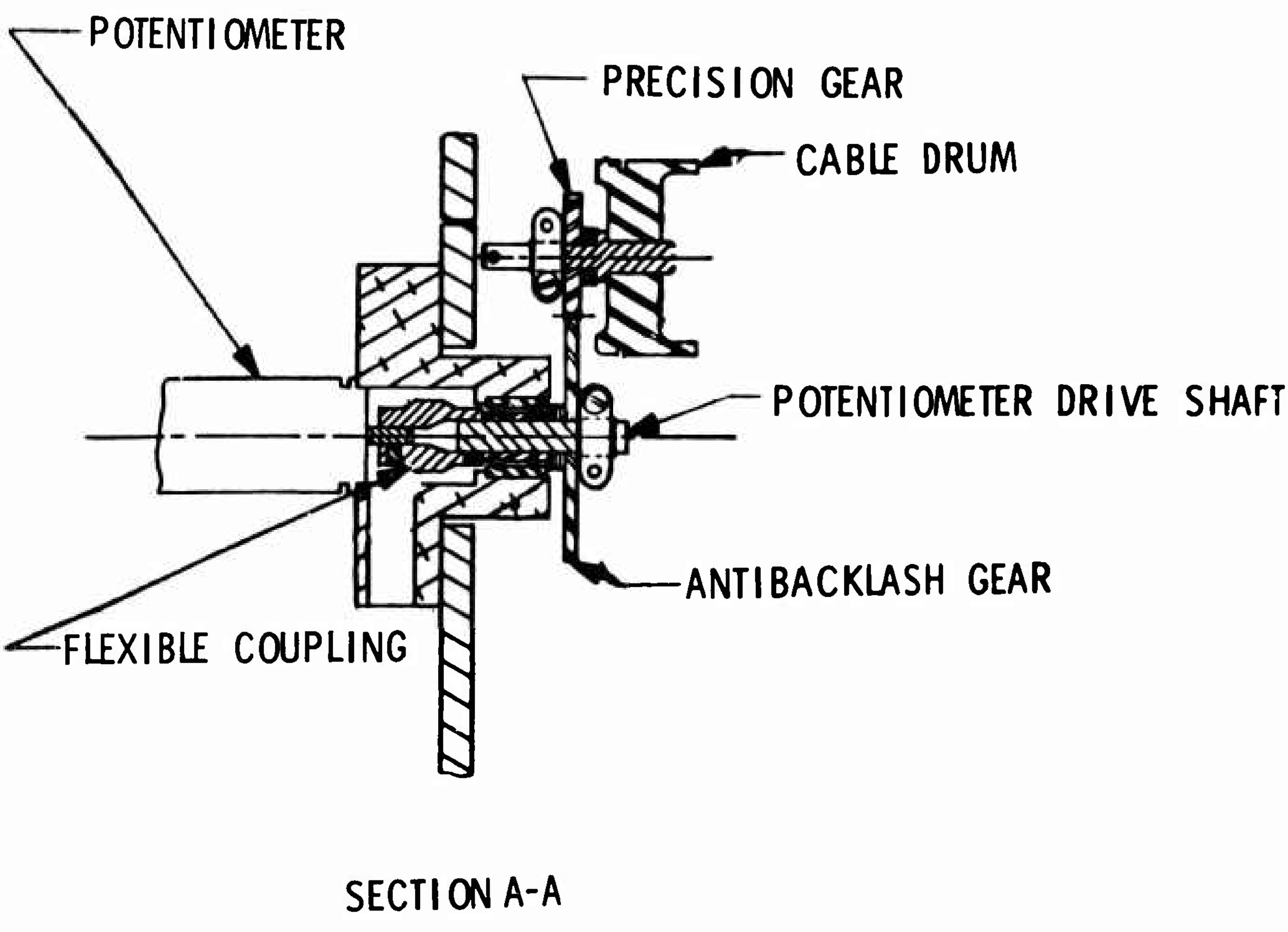
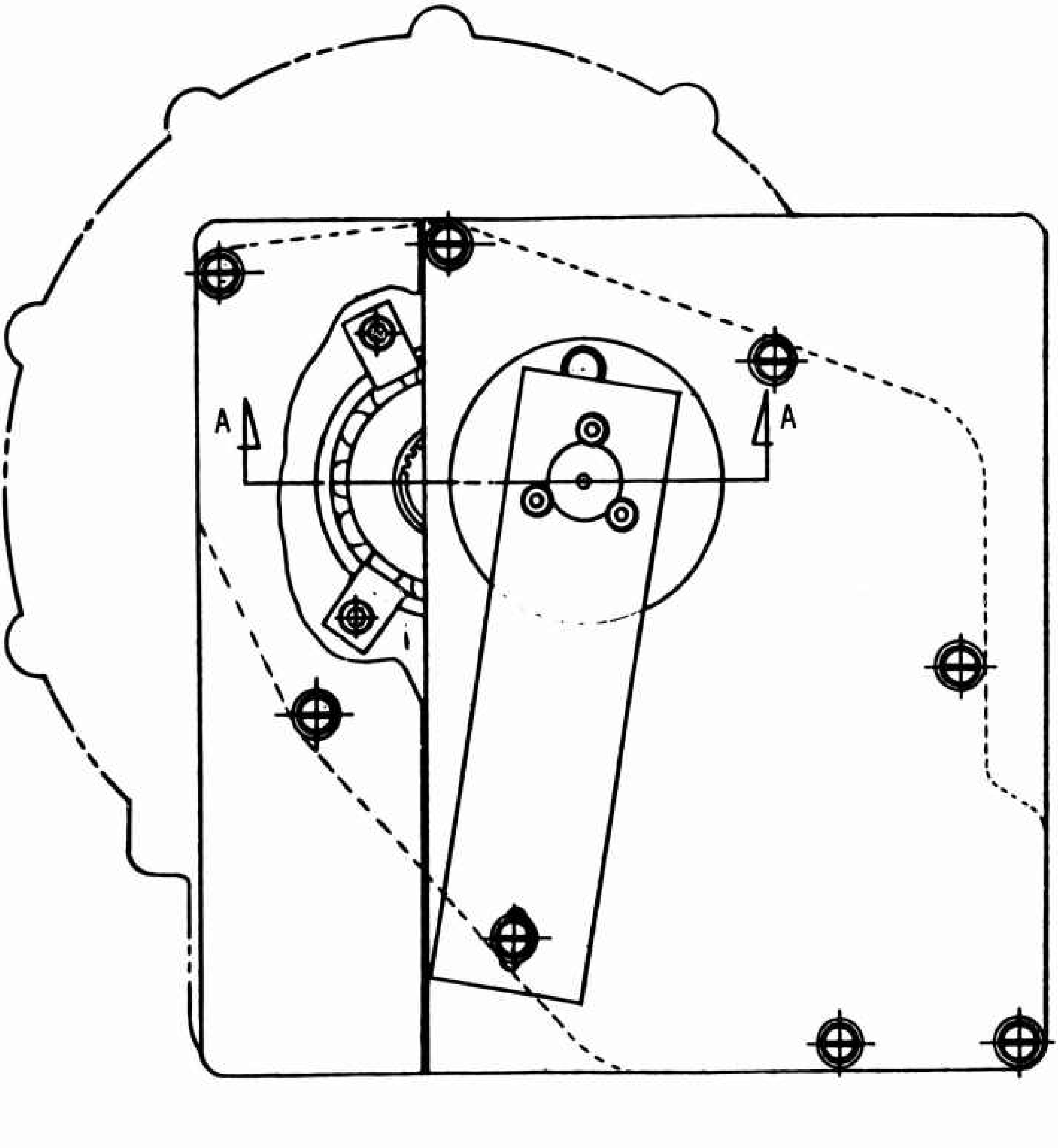



Figure 10. Potentiometer Drive.




B

# STABILITY AND ERROR ANALYSIS

## INTRODUCTION

The accuracy and stability of a four-point synchronized hoist system were investigated analytically to provide the basis for system design. This investigation was used to predict the dynamic and steady-state behavior of four-point hoist systems.

The nonlinearities inherent in electrohydraulic systems, as well as the mathematical difficulties attendant to the system design, suggested a digital simulation to predict dynamic behavior of a platform. The time histories of platform angles could then be compared to steady-state expectations in order to evaluate accuracy and stability criteria.

## DISCUSSION

### Motivation

Certain observations suggest that a static error analysis provides an insufficient description of potential difficulties in operating multipoint hoist synchronized systems. In particular, the following reasoning motivated a dynamic error and stability analysis:

> The system is subject to nonlinear hydraulic effects.
>
> Dynamic effects of changing cable tensions will probably degrade system stability.
>
> Maximum angular deflection of a platform during transient operations may be considerably larger than static deviations.

### Approach

It was decided that a digital computer simulation of the synchronization system provided the only viable means for analysis. This conclusion was based on two observations:

> The system is intensely nonlinear. Analysis techniques for current systems are incapable of an accurate, analytic description of the system.
>
> A unique analytic solution does not exist. The system is necessarily overspecified. A platform which is described by three force and moment equations is suspended by four cables. Hence, there are many combinations of cable tensions that could support

a given load. Since the synchronization system is sensitive to cable tension, many solutions exist for the same load.

Accordingly, a digital computer simulation capable of investigating a variety of load conditions was written.

## ANALYSIS

### Dynamic Analysis Performance Criterion

During hoisting operations, the platform shall remain parallel to the helicopter within ± 5° in roll and pitch. This criterion shall be met for any permissible load distribution and is based on the assumption that platform pitch or roll angle deviations of ± 5° are tolerable for hoisting operations. A ± 5° pitch or roll deviation is not readily discernible to a hoist operator positioned above the load, as he would be in a CH-54A, and most probably would not require corrective beeping. The magnitude of cable length differentials resulting from platform pitch and roll angles of 1°-5° is shown in Table I.

TABLE I. CABLE LENGTH DIFFERENTIALS PER DEGREE OF PITCH OR ROLL

| Pitch Or Roll Angle (deg) | Fore/Aft, Port/Stbd Cable Length Differential (in. /ft of platform length or width) |
|---|---|
| 1 | 0.209 |
| 2 | 0.418 |
| 3 | 0.628 |
| 4 | 0.836 |
| 5 | 1.046 |

### Flow-Divider Operation

Synchronization of the hoists in the system is directly related to the performance of flow dividers, which divide a given flow rate into two parts according to certain criteria. The flow-divider device is shown schematically in Figure 11.

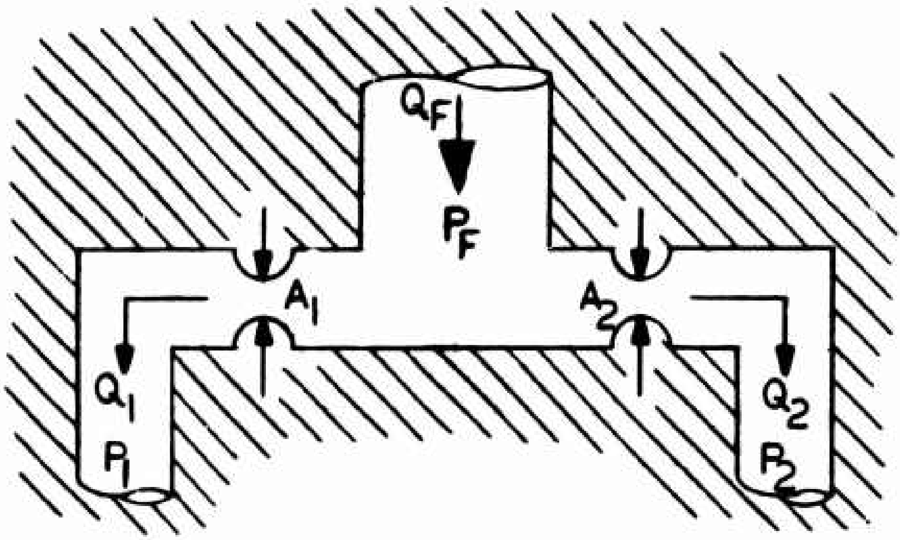



Figure 11. Schematic of Forward Flow Divider.

Input flow, $Q_F$, is divided into two channels. These channels lead to two of the hydraulic hoists. The flow rate through the channels controls the rates at which cables are being reeled in or let out. The pressure in a channel to an individual hoist is proportional to the tension in the hoist cable. Since the flow to hoist 1, $Q_1$, is dependent on the pressure drop $(P_F - P_1)$, the division of flow is load sensitive (i. e., the division of flow will change as cable tensions change). The flow $Q_1$ is also dependent on the area of the variable port $A_1$. Since this area is dependent on the difference in the lengths of cable 1 and cable 2, the division of flow is dependent on the angular position of the platform relative to the aircraft. Thus, the flow divider is both load sensitive and position sensitive. The following equations describe the division of flow:

$$Q_F = Q_1 + Q_2 \tag{1}$$

$$Q_1 = A_1 \ (P_F - P_1)^{\frac{1}{2}} \tag{2}$$

$$Q_2 = A_2 \ (P_F - P_2)^{\frac{1}{2}} \tag{3}$$

Thus, the division of flow is specified, once the parameters $Q_F$, $P_F$, $A_1$, $A_2$, $P_1$, and $P_2$ are known.

## Overall System Operation

The four-point synchronization system utilizes three flow dividers as shown in Figure 12.

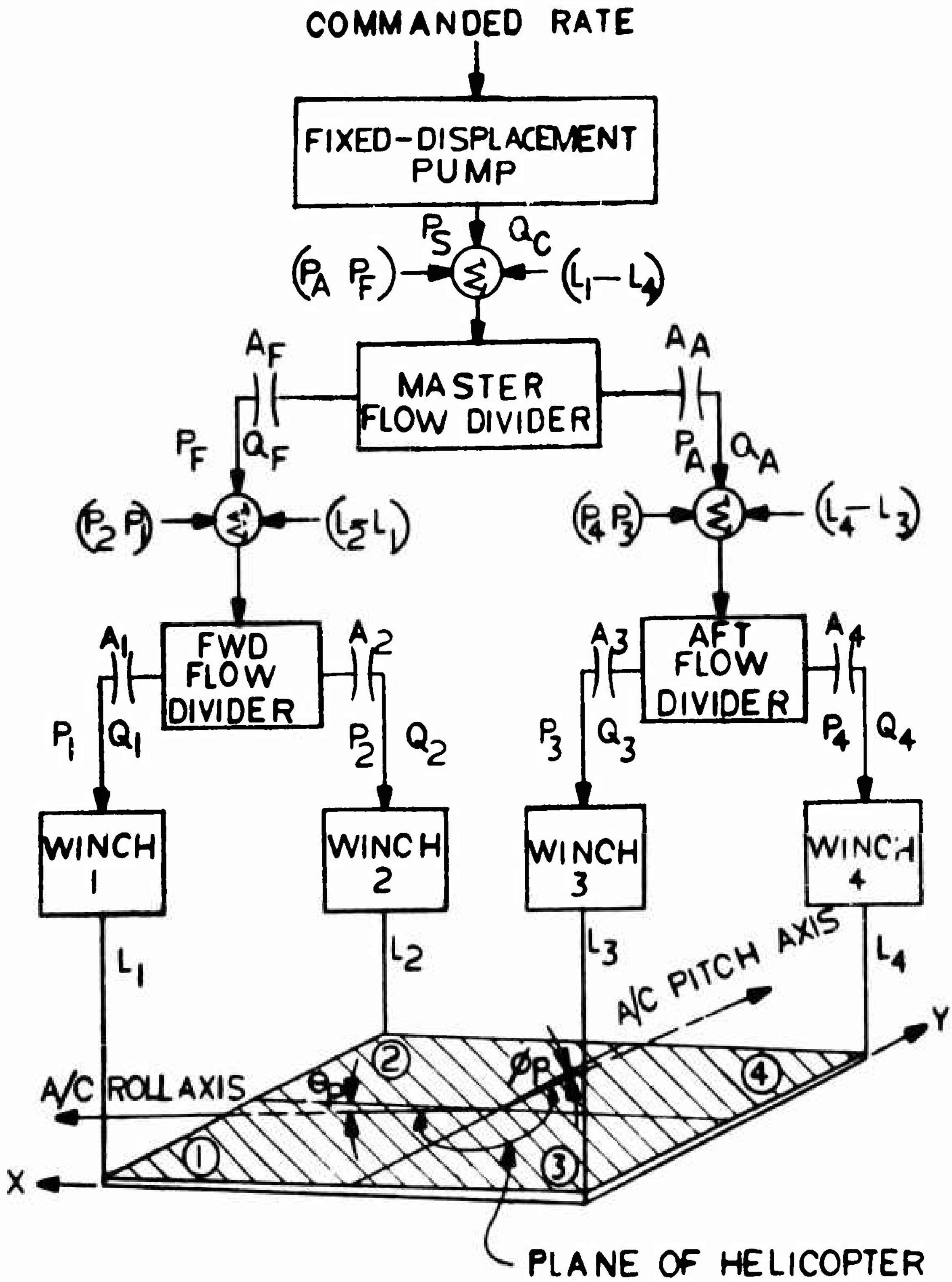



Figure 12. Schematic of Overall System.

The following set of equations describes the overall division of flow:

$$Q_C = Q_A + Q_F \tag{4}$$

$$Q_F = Q_1 + Q_2 = A_F \ (P_S - P_F)^{\frac{1}{2}} \tag{5}$$

$$Q_A = Q_3 + Q_4 = A_A \ (P_S - P_F)^{\frac{1}{2}} \tag{6}$$

$$Q_1 = A_1 \ (P_F - P_1)^{\frac{1}{2}} \tag{7}$$

$$Q_2 = A_2 \ (P_F - P_2)^{\frac{1}{2}} \tag{8}$$

$$Q_3 = A_3 \ (P_A - P_3)^{\frac{1}{2}} \tag{9}$$

$$Q_4 = A_4 \ (P_A - P_4)^{\frac{1}{2}} \tag{10}$$

This above set of equations may be reduced to a set of five equations in seven unknowns:

$$\left.\begin{aligned} Q_C &= A_F \ (P_S - P_F)^{\frac{1}{2}} + A_A \ (P_S - P_A)^{\frac{1}{2}} \\ Q_1 &= A_1 \ (P_F - P_1)^{\frac{1}{2}} \\ Q_2 &= A_2 \ (P_F - P_2)^{\frac{1}{2}} \\ Q_3 &= A_3 \ (P_A - P_3)^{\frac{1}{2}} \\ Q_4 &= A_4 \ (P_A - P_4)^{\frac{1}{2}} \end{aligned}\right\} \tag{11}$$

where, at any instant, $P_S$, $P_F$, $P_A$, $Q_1$, $Q_2$, $Q_3$ are unknown, $P_1$, $P_2$, $P_3$, $P_4$ are known functions of cable tension, and the flow-divider port areas are functions of the differential cable lengths as shown in Figure 13.

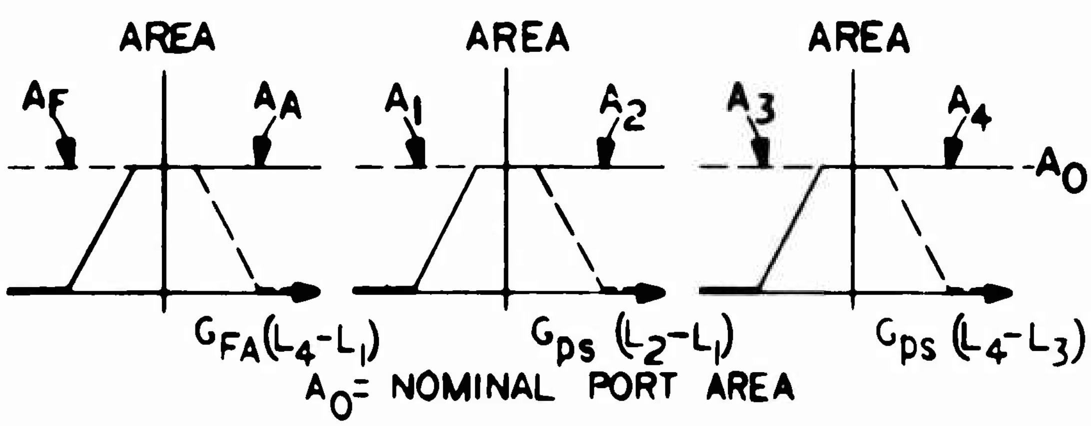



Figure 13. Variable Restriction Areas as a Function of Differential Cable Lengths.

The flow-divider port areas are nonlinear functions of the differences in cable lengths. Moreover, the square root characteristic in the flow

equations leads to simultaneous equations describing the allocation of flow at any instant.

In addition, the following constraints result from characteristics of the hoist. A $\delta(i)=0$ implies that hoist (i) has stalled and that there is no flow in channel i.

$$\left.\begin{array}{ll} P_F < P_1 \; ; & \delta(1) = 0 \\ P_F < P_2 \; ; & \delta(2) = 0 \\ P_A < P_3 \; ; & \delta(3) = 0 \\ P_A < P_4 \; ; & \delta(4) = 0 \end{array}\right\} \quad (12)$$

Otherwise $\delta(i) = 1$, $i = 1, 2, 3, 4$

These nonlinearities and constraints preclude an analytic expression for the division of flow. However, they are amenable to an iterative solution on a digital computer.

Since the supply pressure varies widely as a function of demand, while the supply flow rate remains constant, the technique shown in Figure 14 is used to determine the allocation of flow at any instant.

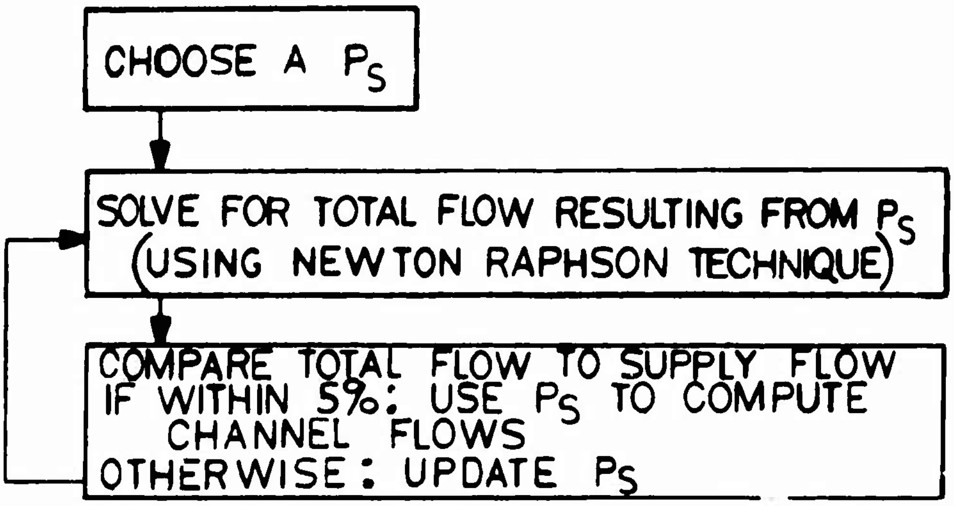



Figure 14. Technique Used To Compute Allocation of Flow.

The flow rate at a given instant determines hoisting rates and hence the cable position an instant later. Certain assumptions on the dynamic characteristics of the platform allow the cable tensions at the next iteration to be computed. New cable positions and new cable tensions are used to update flow allocation, and the process continues until the platform has been raised or lowered the specified amount.

Figure 15 shows the computer flow diagram for the simulation. The names in parentheses refer to subroutine names. A listing of the program has been prepared.[4]

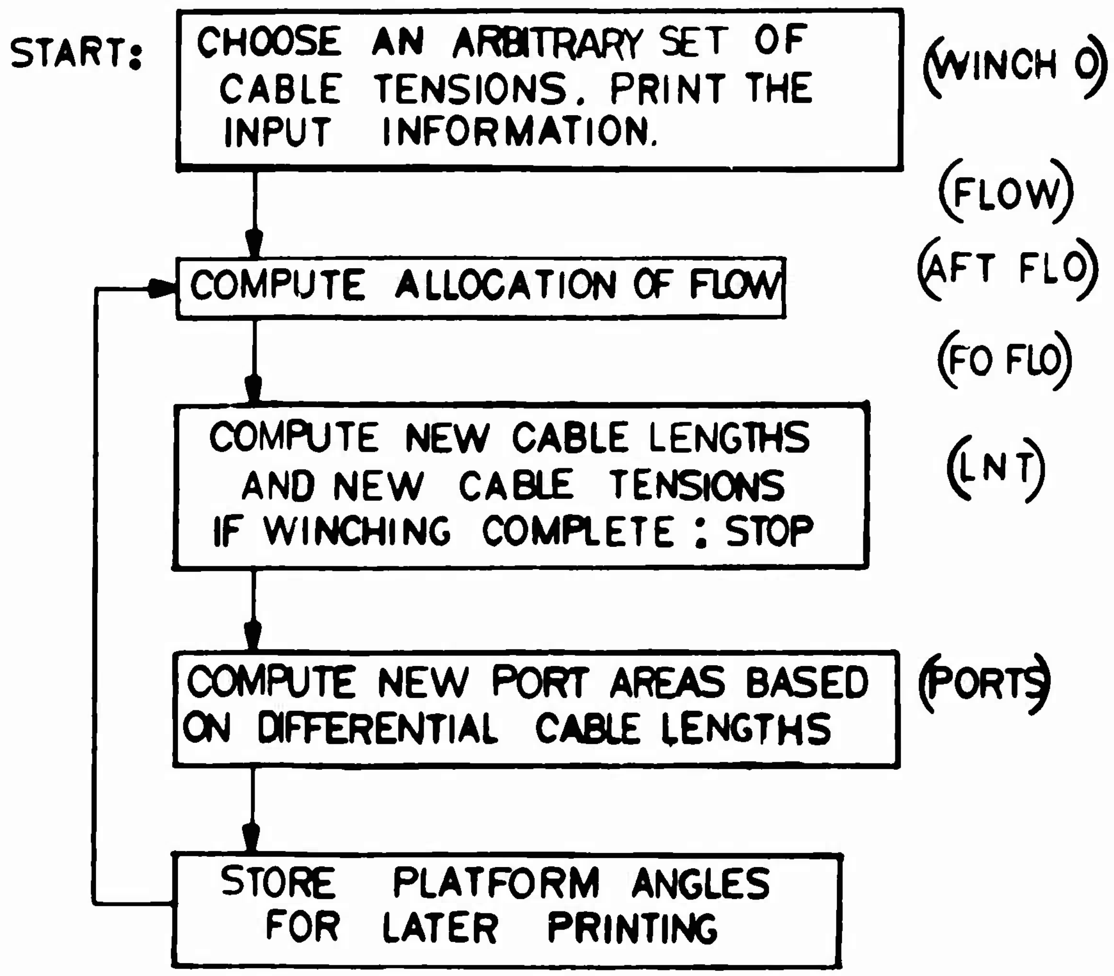



Figure 15. Computer Flow Diagram for Four-Point Hoist Simulation.

With the results of the computer simulation for various conditions, system characteristics may be observed These characteristics are reported in the "Results" section which follows.

Static Analysis

The expected steady-state platform angles will be a function of the following system parameters:

1. Load weight

2. Load position on platform. The range of cable tensions that will support a given load is a function of load position. Since hoist pressure is proportional to cable tension, a range of pressures is also possible; hence, the steady-state platform angles will fall within a predictable range. The relevant system parameters are:

   a. Maximum supply pressure

   b. Rated overall load

3. Commanded hoist rate (proportional to commanded flow), which depends on:

   a. Rated flow

   b. Rated hoist rate

Given the information above, the steady-state platform angles can be computed if the following observations are made:

The flow rate to each hoist is equal.

At least one port in each flow divider is wide open.

If the load center of gravity is in quadrant 1 of the platform (see Figure 16), then the following relations determine the steady-state platform angle. A similar analysis yields the steady-state conditions for other load conditions.

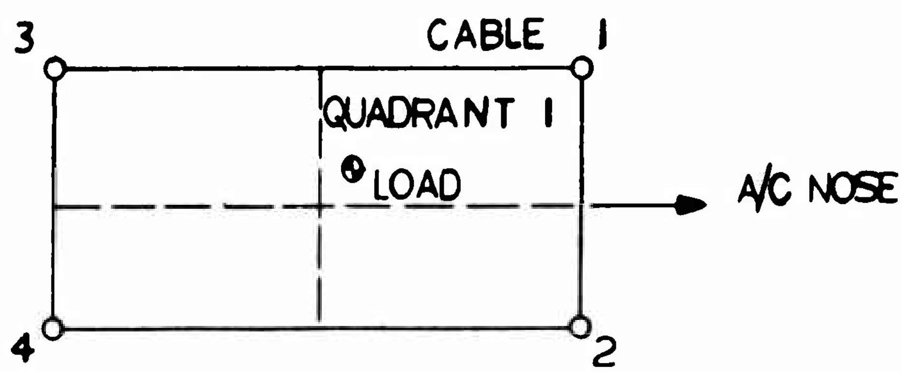



Figure 16. Division of Platform Into Quadrants.

For load cg in first quadrant:

$$Q_A = Q_F = Q_C/2 \tag{13}$$

$$A_F\ (P_S - P_F)^{\frac{1}{2}} = A_A\ (P_S - P_A)^{\frac{1}{2}} = Q_C/2$$

$$Q_1 = Q_2 = Q_3 = Q_4 = Q_C/4 \text{ (Observation 1)}$$

$$\begin{aligned} A_1\ (P_F - P_1)^{\frac{1}{2}} &= A_2\ (P_F - P_2)^{\frac{1}{2}} \\ &= A_3\ (P_A - P_3)^{\frac{1}{2}} = A_4\ (P_A - P_4)^{\frac{1}{2}} \end{aligned} \tag{14}$$

$$A_1 = A_4 = A_F = A_0 \text{ (Observation 2 for first quadrant)} \tag{15}$$

where

$$\left.\begin{aligned} A_O &= Q_{max}/(P_{Smax})^{\frac{1}{2}} \\ Q_C &= \text{RATE } Q_{max}/\text{RATE}_{max} \\ P_1 &= \text{CST } (T_1) \\ \text{CST} &= 2\ P_{Smax}/\text{LOAD}_{max} \\ T_1 &= \text{Tension in cable 1} \end{aligned}\right. \tag{16}$$

From equations (15), (14), and (13),

$$\left.\begin{aligned} A_A &= (Q_C/2)\ \ (Q_C{}^2/4A_O{}^2) + (P_1 - P_4)^{\frac{1}{2}} \\ A_2 &= (Q_C/4)\ \ 1.25\ \ (Q_C{}^2/4A_O{}^2) + (P_1 - P_2)^{\frac{1}{2}} \\ A_3 &= (Q_C/4)\ \ 1.25\ \ (Q_C{}^2/4A_O{}^2) + (P_3 - P_4)^{\frac{1}{2}} \end{aligned}\right\} \tag{17}$$

From the relationships defined in Figure 12,

$$\left.\begin{aligned} (L_2 - L_1) &= 6\ (A_2 - A_O)\ /\ A_O G_{ps} \\ (L_4 - L_3) &= -6(A_3 - A_O)\ /\ A_O G_{ps} \\ (L_4 - L_1) &= 6(A_A - A_O)\ /\ A_O G_{FA} \end{aligned}\right\} \tag{18}$$

And the steady-state platform angles follow from the definitions

$$\begin{aligned} \theta p &= (L_1 + L_2) - (L_3 + L_4)\ \ (57.3/40) \\ \phi p &= (L_1 + L_3) - (L_2 + L_4)\ \ (57.3/20) \end{aligned} \tag{19}$$

The derivation of equation (18) is described below.

Figure 12 shows the port area in the flow divider as a function of the current into the valve. The current is a gain times a differential cable length:

$$ma = G_{ps}\ (ma/ft)\ (L_2 - L_1) \tag{20}$$

The port has a maximum area of $A_O$ and a minimum of zero if the assumptions are made that: the flow divider saturates at 6 ma, the port is neither wide open nor closed off (conditions 13, 14, 15), and there is zero deadband in the valve.

Then we have the idealized flow-divider characteristic shown in Figure 17.

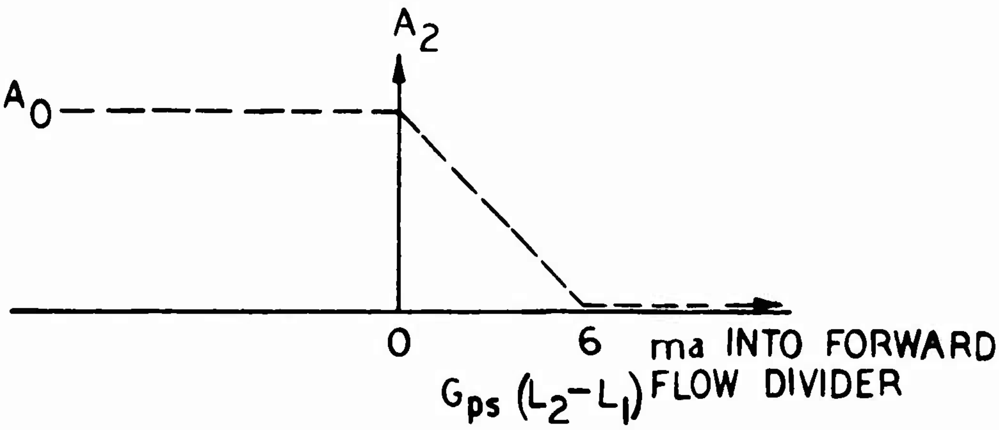



Figure 17. Idealized Flow-Divider Characteristic.

The equation for the region of interest, $0 \leq ma \leq 6$, is

$$A_2 = (-A_O/6)G_{ps}\ (L_2 - L_1) + A_O \tag{21}$$

or, solving for the differential length,

$$(L_2 - L_1) = -6(A_2 - A_O)/A_O G_{ps} \tag{18}$$

This equation is then used in equation (19) to compute static platform angles.

## RESULTS

### A Typical Transient

Figure 18 shows platform angles as a function of time for the following conditions:

| | |
|---|---|
| Rated Flow | 11 gpm |
| Rated Supply Pressure | 2550 psi |
| Rated Hoist Rate | 100 fpm |
| Rated Load - Overall | 2400 lb |
| Commanded Hoist Rate (load is being hoisted in) | 80 fpm |
| Load | 1500 lb |
| Load Position (cg) | $cg_x$ = 11 ft |
| | $cg_y$ = 3 ft |
| Feedback Gains | Fore-Aft 12 ma/ft<br>Port-Stbd 6 ma/ft |

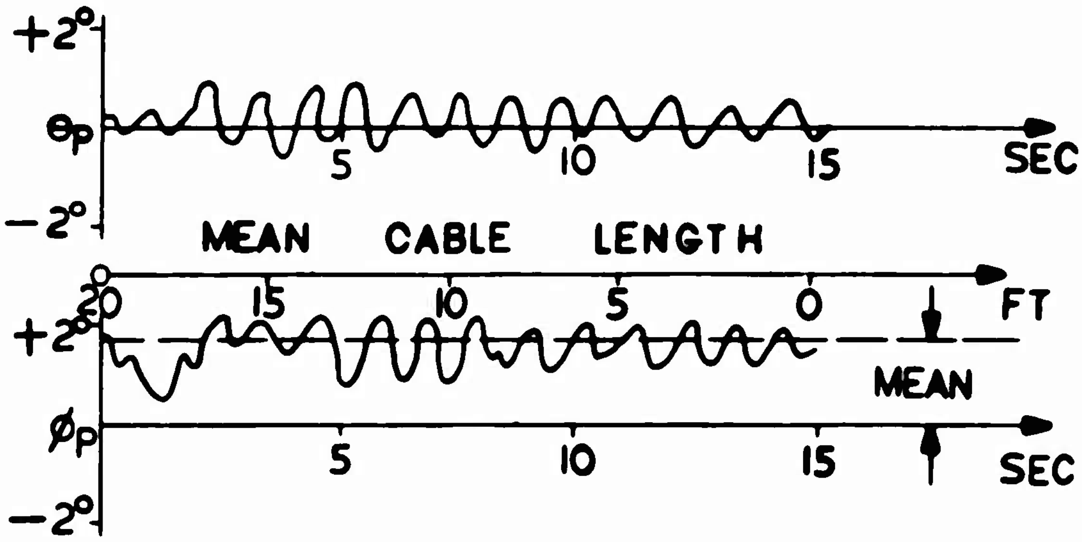



Figure 18. A Typical Transient.

Hoisting Time as a Function of Load

Because the system does not utilize ideal flow regulators, heavy loads take longer to reel in. Moreover, in lifting heavy asymmetric loads, the hoists supporting the major load fraction occasionally stall. Figure 19 shows these characteristics.

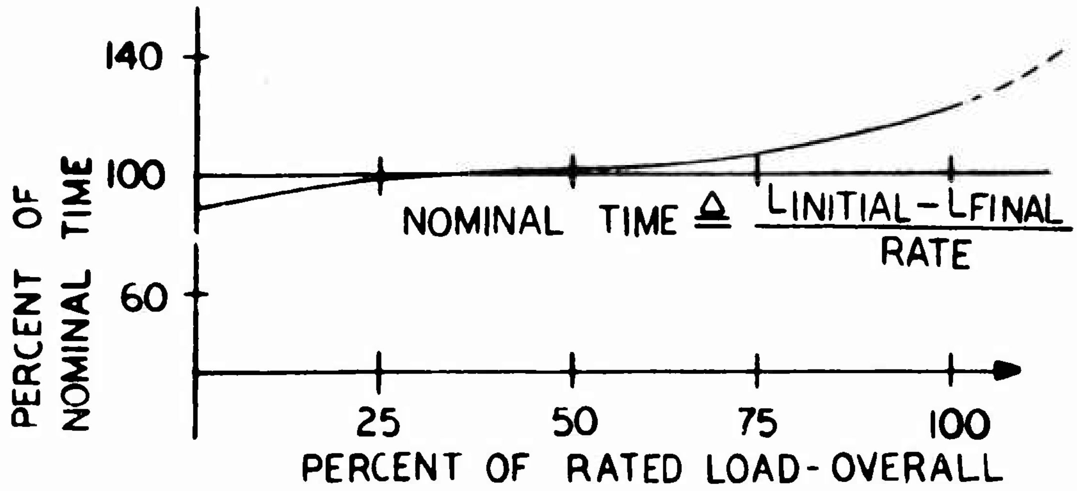



Figure 19. Hoisting Time as a Function of Load.

<u>Expected Steady-State Angles as a Function of Load Position for a Given Load (Via Static Analysis)</u>

From the static analysis, isograms may be drawn for the loci of steady-state platform angles as a function of load position. In every instance they represent the worst-case steady state, resulting from the most unevenly distributed static cable tensions. Figure 20 illustrates these isograms.

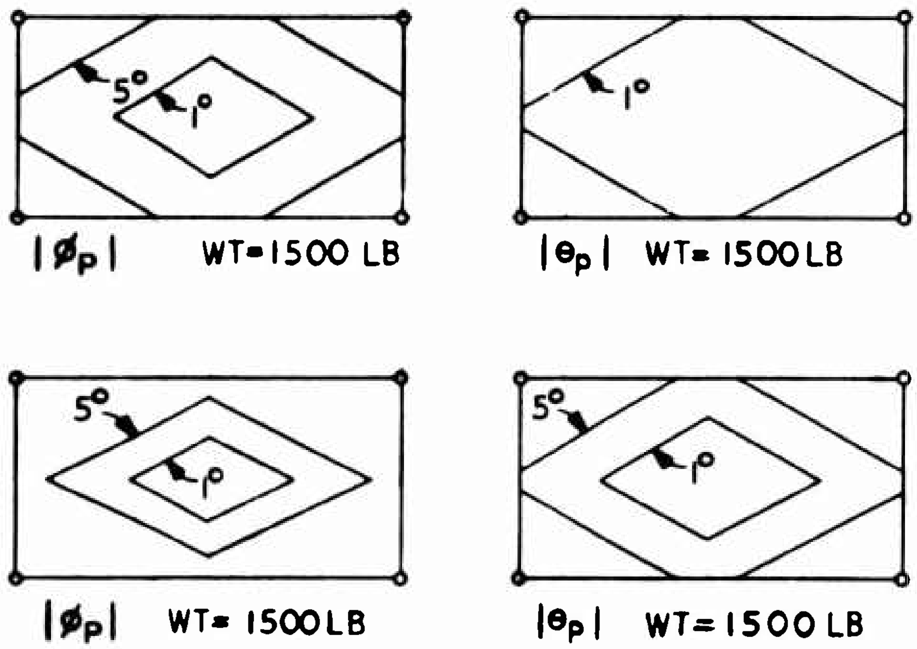



Figure 20. Loci of Expected Steady-State Platform Angles as a Function of Load Position for a Given Load.

Empirical Mean Steady-State Platform Angles as a Function of Load Position for a Given Load (Via System Simulation)

Through the use of the system simulation, the following platform angle-load position characteristics were found for a 1500-lb load. The steady-state mean angle is the average value over several cycles of steady-state oscillation (if any). These characteristics are shown in Figure 21.

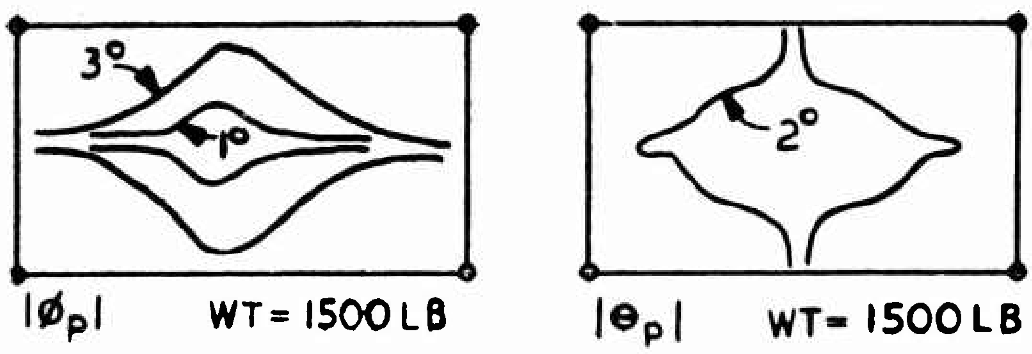



Figure 21. Loci of Empirical Mean Steady-State Platform Angles as a Function of Load Position for a Given Load.

Steady-State Platform Oscillations

Steady-state platform angles exhibited periodic oscillation for some load conditions. In general, three variables were found to have an effect upon the amplitude and frequency of the oscillation:

Load weight: The following relationship was observed between load weight and oscillation amplitude. In all observed oscillations, the frequency was approximately 1 cps. Oscillation amplitudes are shown in Figure 22.

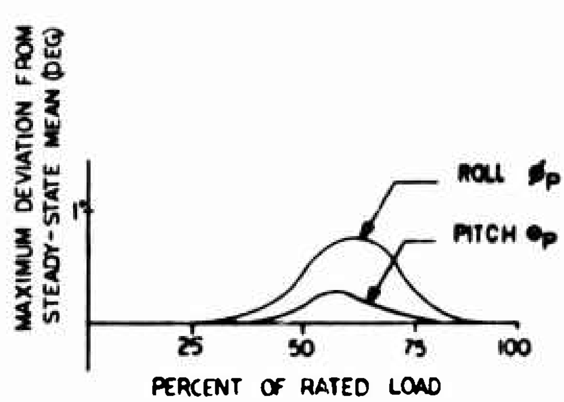



Figure 22. Platform Oscillations Due to Load Weight.

Load position: Load position was found to have an effect on platform oscillations similar to the effect of load weight. Define the quantity

$$R = [2(10-cg_x)^2 + (5-cg_y)^2]^{\frac{1}{2}} \tag{22}$$

Then, for a 1500-lb load, the oscillation amplitude varied with R approximately as shown in Figure 23. The frequency was nearly constant at 1 cps. These data are illustrated in Figure 23.

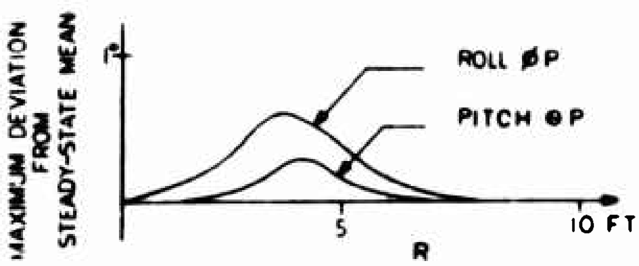



Figure 23. Effect of Load Position on Steady-State Oscillation Amplitude.

Feedback gains: Increasing the roll feedback gain, $G_{ps}$, by a factor of 2 had the effect of halving the oscillation amplitude and doubling the oscillation frequency both in roll and in pitch. A similar effect was observed for changes in the pitch feedback gain, $G_{FA}$. The gain settings specified for the typical transient case were found to be the best empirical compromise between oscillation amplitude and frequency.

### Hoisting Direction

The results presented in this report are for a load being reeled in. The simulation indicated that system behavior is somewhat degraded for the case where a load is being payed out. However, these data are deemed to be unreliable since it was not possible to include the effect of hoist brakes in the simulation.

## CONCLUSIONS

### Stability

The four-point hoist system, with the parameters specified in the typical transient case, will be stable in both pitch and roll. Limit cycle oscillations may be expected for some load conditions, but in all cases such oscillation will not exceed $4^\circ$ peak-to-peak amplitude at approximately 1 cps.

Accuracy

It will be possible to meet the performance criterion of $\pm 5^{o}$. The least accurate case will be for a medium-weight (i.e., one-half maximum rated weight) asymmetric load, in which case the largest error observed will be $\pm 5^{o}$.

Uncertainty

Because the system is necessarily overspecified, as explained in the discussion, tests on a mock-up may not be repeatable but should fall within the limits stated above.

# TEST PROGRAM

## INTRODUCTION

The test procedure formulated for the four-point synchronized hoist was designed to evaluate the electrohydraulic circuit and the analytical analysis used to predict the performance of the system. Relative cable length differences were measured and recorded. The accumulated test data were used in a statistical analysis to determine repeatability and accuracy of the four-point system. Test data were compared with data generated in the analytical error analysis.

## TEST APPARATUS

Four modified rescue hoists were mounted in a rectangular pattern, 6 ft by 8 ft center to center, 23 ft high.

The hoists were mounted on the platform that had been utilized to test the CH-54A four-point hoist system. A photograph of the hoisting platform is shown in Figure 24.

An 8-by-5-ft load pallet, designed in identical geometric proportions as that proposed for the aerial platform to be used with the S64B HLH helicopter, and weights, in 200-lb blocks, to be used in testing the model system were fabricated.

Dynamics of the proposed aerial platform were simulated in the model hoisting platform. The platform moments of inertia in the longitudinal and latitudinal directions were chosen such that the platform stiffness/working load ratio was identical to that proposed for the CH-54B aerial platform. The dynamic response of the CH-54B aerial platform would be similar to that experienced by the model system since the stiffness/working load parameters of the model system are in the same proportions as those of the proposed CH-54B system.

A more realistic model of the proposed CH-54B system would include load isolators at each hoist mount. A model with all dynamic parameters in proportion to those of a proposed aircraft system would exhibit dynamic properties identical to those of the aircraft system.

Manometers mounted at each corner of the load pallet were used to measure relative displacements of platform corners.

Dynamic characteristics were recorded on an oscillograph. The data recorded were the traces of the potentiometer output voltages.

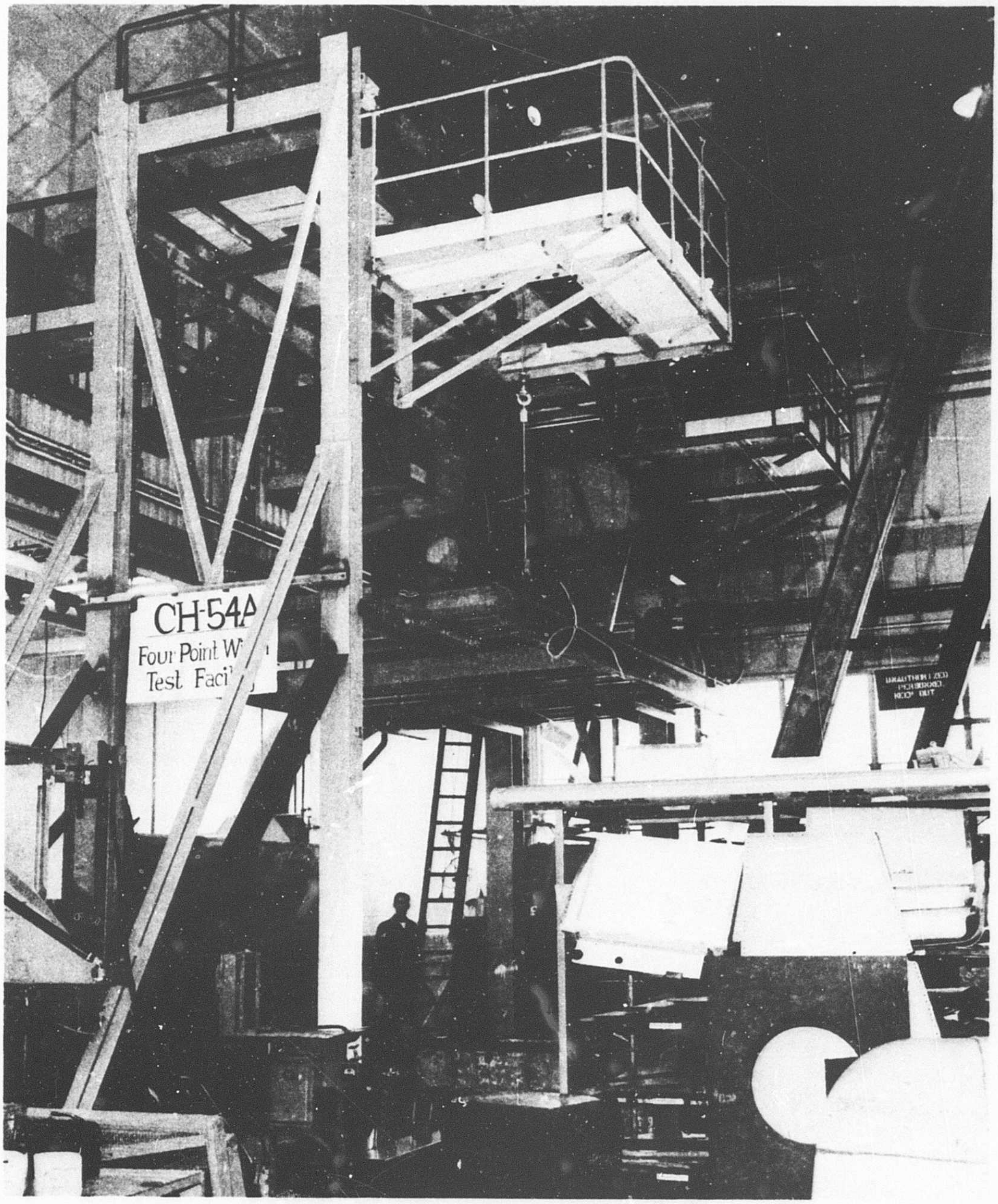



Figure 24. Hoisting Platform.

## TEST PROCEDURE

The plan utilized in testing the prototype synchronized multipoint hoist consisted of three distinct phases: test and development of the single hoist; test, development, and optimization of the four-point hoist; and tests of repeatability and accuracy of the four-point hoist.

### Individual Hoist Tests

Pertinent data, hook speed, hook movement per hoist drum revolution, and cable stretch under load were measured and recorded to determine the effect of inherent hoist variations on cable length excursions due to hoist tolerances and hoist loading.

### Development Test

Due to poor performance of hoists during individual hoist tests when individual hoist loads exceeded 200 lb, synchronized lifts were limited to load configurations that did not result in single hoist loads exceeding 200 lb. Components were adjusted and modified to minimize differential cable lengths and to obtain optimum running characteristics. No fixed loading was adhered to because adjustments and modifications were made only as required. Error-reduction tests were combined with the development tests. Because of the high-performance characteristics of operational amplifiers (linearity and reliability) incorporated in the feedback control circuit, trimming pots, which were originally considered for reduction of errors, were not considered because they could not perform any significantly useful function. Error reduction was accomplished by adjusting the gain of operational amplifiers while running with various loads and cg's.

### System Evaluation Test

Due to unsuccessful operation of the hoists (spasmodic chattering and jerking) when lowering load configurations that imposed a load in excess of 200 lb on any single hoist, Sikorsky Aircraft could not use the originally proposed development and evaluation test plan.[5]

The test plan used in the evaluation phase includes more cycles than the originally proposed test plan, 185 versus 150, but there are fewer load configurations, 16 versus 25. The final test plan was specifically arranged such that the maximum amount of information could be obtained for inclusion in a statistical analysis.

The system evaluation test was conducted as follows:

> For each run, with the hoisting platform leveled at its lowest suspension position, manometer readings were recorded; i. e., relative hook/corner relationships were noted.
>
> At the maximum height of each run, manometer readings were again taken.
>
> The platform was lowered to its lowest suspended position, and manometer readings were again taken.
>
> During random runs during the 40-cycle test, as the platform was being raised, a continuous record of the signals to each flow-divider valve was taken on the oscillograph.

Variations in load weight and center of gravity were achieved by placing 200-lb weights in certain combinations on a test platform, as shown in Figure 25 and Table II.

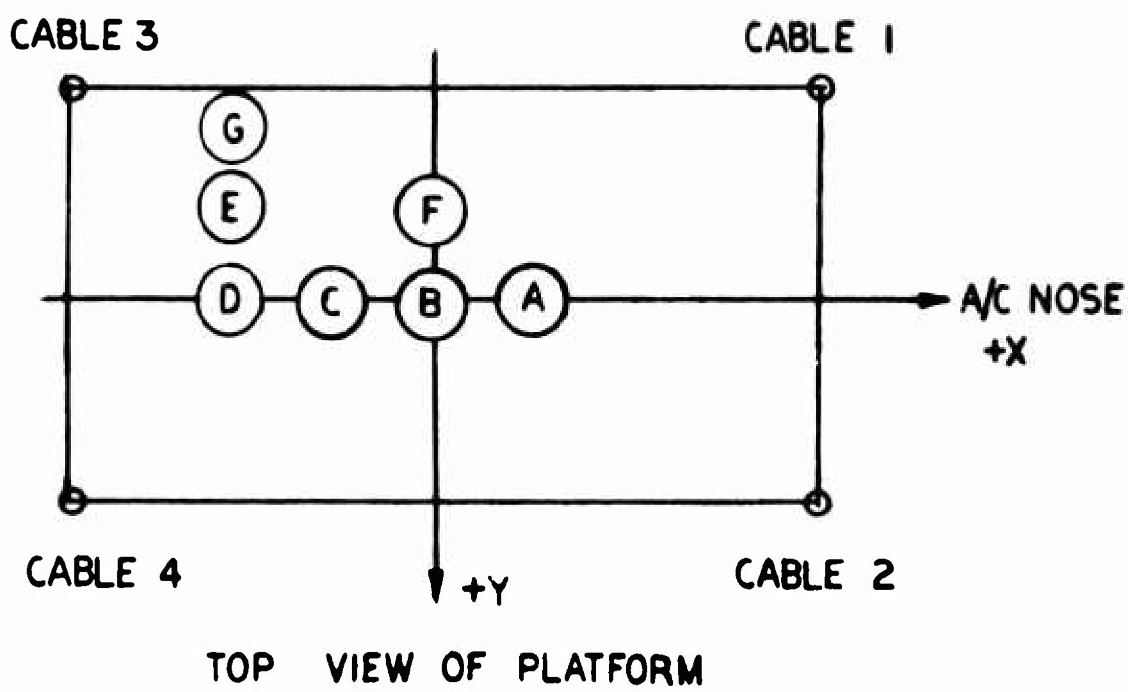



Figure 25. Load Positions on Platform.

TABLE II. LOADING CONDITIONS FOR SYSTEM EVALUATION TEST

| Case Number | Position for 200-lb Weights A | B | C | D | E | F | G | Number of Cycles | Center of Gravity $cg_x$ | $cg_y$ | Total Load (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | No Weights | | | | | 5 | 0 | 0 | 0 |
| 2 | | | | X | | | | 5 | -31.8 | 0 | 200 |
| 3 | | | | | X | | | 40 | -20.0 | -11.5 | 200 |
| 4 | | | | | | X | | 5 | 0 | -18.1 | 200 |
| 5 | | | | | | | X | 5 | -19.4 | -18.1 | 200 |
| 6 | | X | | | | | | 5 | 0 | 0 | 200 |
| 7 | | X | | X | | | | 5 | -18.3 | 0 | 400 |
| 8 | | X | | | X | | | 40 | -11.5 | - 6.6 | 400 |
| 9 | | X | | | | X | | 5 | 0 | -10.4 | 400 |
| 10 | | X | | | | | X | 5 | -10.3 | -10.4 | 400 |
| 11 | X | | X | | | | | 5 | 0 | 0 | 400 |
| 12 | X | | X | X | | | | 5 | -13.0 | 0 | 600 |
| 13 | X | | X | | X | | | 40 | - 8.2 | - 4.7 | 600 |
| 14 | X | | X | | | X | | 5 | 0 | - 7.4 | 600 |
| 15 | X | | X | | | | X | 5 | - 9.0 | - 7.4 | 600 |
| 16 | X | X | X | | | | | 5 | 0 | 0 | 600 |

## TEST RESULTS

### Single-Point Hoist Evaluation

Individual tests at loads up to 600 lb were included in the originally proposed test plan.[5] Due to poor performance of the hoists when loads were greater than 200 lb, individual hoist tests were limited to loads of 200 lb.

Cable speed and test results are listed in Table III.

### Cable Stretch Under Load

$$\text{Stretch}_{(\text{in.})} = (l/20)(wt/635) \tag{23}$$

where $l$ = length of cable, ft
$wt$ = weight of load, lb

A general formula for determining the elastic stretch of a cable under load is

$$e = (wt)(l)/AE \tag{24}$$

where $e$ = elastic stretch, ft
$wt$ = weight of load, lb
$l$ = length of cable under load, ft
$A$ = cable metallic area, in.$^2$
$E$ = modulus of elasticity, psi

Cable stretch encountered in Sikorsky Aircraft cargo hoist applications is as follows:

CH-54A main cargo hoist - 0.5% at maximum working load
CH-54A four-point cargo hoist - 0.38% at maximum working load

Although the cable speeds for different hoists vary, the effect of speed variations on system accuracy is negated by the system feedback loop. The variations in cable speed vividly demonstrate the differences in individual hoist performance.

Hook movement per hoist drum revolution was 25 inches per revolution for all hoists; therefore, although this possible source of cable length error is outside the feedback loop (that due to drum and cable diameter tolerances), it has no effect on the outcome of the system test because there is no measurable error.

TABLE III. CABLE SPEED - INDIVIDUAL HOISTS

| Hoist Number | Hoisting Direction | Cable Load (lb) | Cable Speed (fpm) |
|---|---|---|---|
| 1 | Up | 0 | 118 |
| 1 | Down | 0 | 118 |
| 1 | Up | 129 | 118 |
| 1 | Down | 129 | 118 |
| 1 | Up | 200 | 103 |
| 1 | Down | 200 | 100 |
| 2 | Up | 0 | 109 |
| 2 | Down | 0 | 105 |
| 2 | Up | 129 | 109 |
| 2 | Down | 129 | 111 |
| 2 | Up | 200 | 109 |
| 2 | Down | 200 | 118 |
| 3 | Up | 0 | 118 |
| 3 | Down | 0 | 118 |
| 3 | Up | 129 | 111 |
| 3 | Down | 129 | 120 |
| 3 | Up | 200 | 113 |
| 3 | Down | 200 | 125 |
| 4 | Up | 0 | 122 |
| 4 | Down | 0 | 120 |
| 4 | Up | 129 | 113 |
| 4 | Down | 129 | 120 |
| 4 | Up | 200 | 113 |
| 4 | Down | 200 | 120 |

## Development Tests

The development tests consisted primarily of adjusting components and modifying the system. Feedback gains were adjusted during the testing of various load schemes to ensure system optimization.

During the lowering of a load configuration that imposed a load of 200 lb or more on one hoist, the modified rescue hoists exhibited erratic braking behavior while operated collectively or beeped. Such loads oscillated spasmodically during lowering. Loads weighing less could be lowered and stopped with no erratic behavior.

Failure of the hoist load brake to function properly, particularly during lowering, was obvious. Examination and adjustment of the brakes did not improve their performance.

In order to supplement the hoist brake and to prevent cavitation in case of brake failure, an independent 100-psi source was applied to both sides of the system to establish a minimum system pressure above zero in all lines during any lowering or raising operation.

Due to the reduction in hoist loading that was necessitated in order to complete the test program, pressure levels required to raise loads were significantly lower than those which would have been developed if the original test plan had been adhered to. The system was supercharged to raise pressure in the lines and thereby to include the effects of hydraulic fluid compressibility.

## System Evaluation Test

### Steady State

The steady-state evaluation utilized the manometer readings to establish cable differentials and to compute platform angles.

Steady-state data for each run of the test are listed in the appendix. Table IV shows the cable length differential in inches for each run.

Table V contains platform angles for each run. The differential cable length data were converted to platform angles per equation (19).

### Transient

The oscillograph readings were utilized to establish transient errors. Figure 26 shows a typical oscillograph recording of differential cable length during ascension of the platform. The run shown is number 7. This figure should be compared with Figure 18.

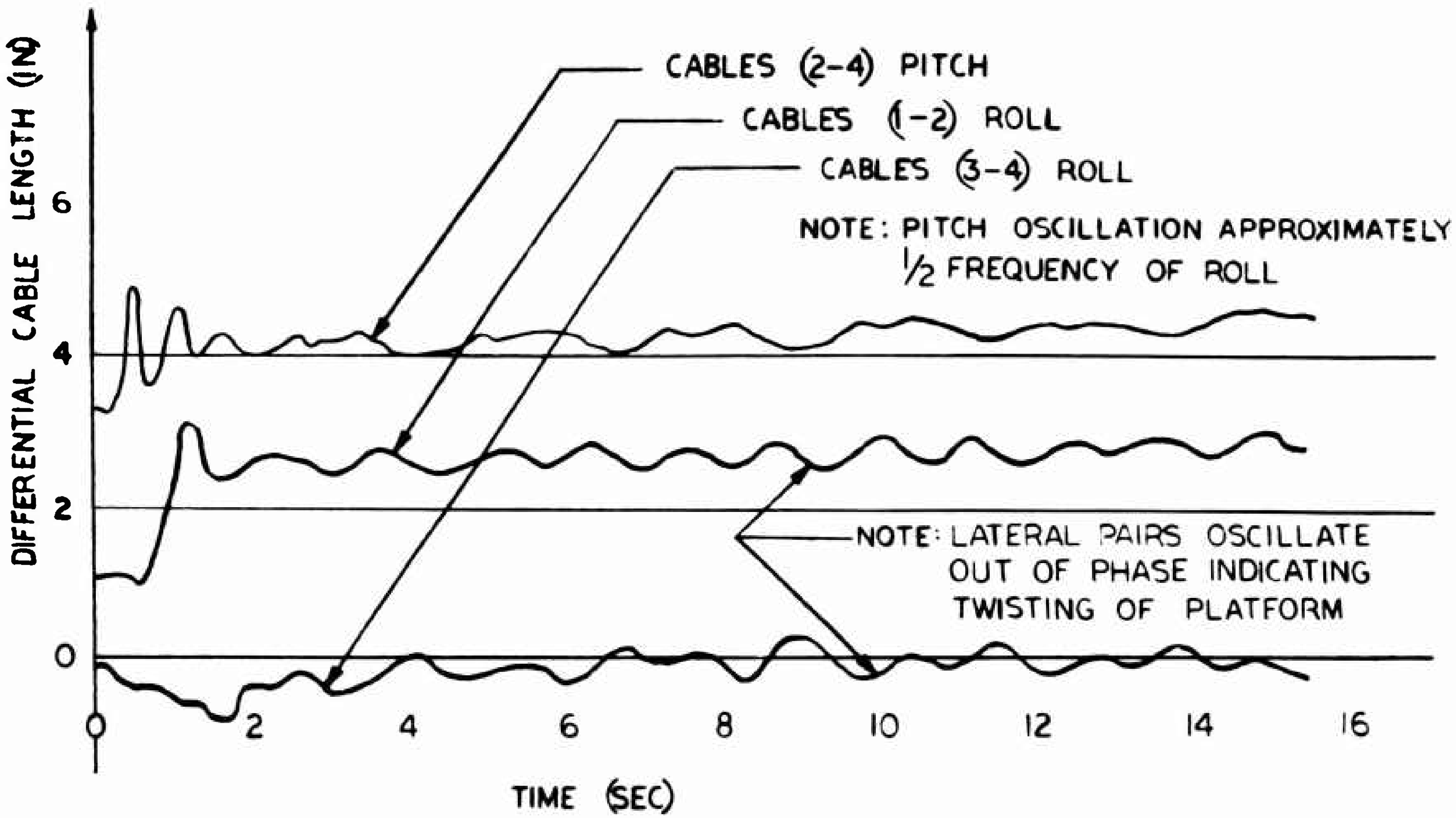



Figure 26. Trace of Oscillograph Data Showing Differential Cable Lengths as a Function of Time.

## EVALUATION AND DISCUSSION OF ERRORS

### INHERENT ERRORS

There are inherent errors in the hoisting system due to drum and cable diameter variations, sensing element tolerances, and hysteresis in control system components. These quantities cannot be compensated for by the feedback system, as either they are outside the feedback loop or they act to decrease system sensitivity. There are two categories of errors: steady-state errors, which are independent of cable travel, and dynamic errors, which are proportional to the amount of cable payed out.

The sources and magnitude of errors according to classifications are listed below:

**Errors Dependent on Cable Travel**

| Source | Error Per Foot of Cable Travel |
|---|---|
| Cable Drum Diameter Tolerance, Root Diameter = 7.797 ± .003 in.<br>Cable Diameter Tolerance, Cable Diameter = 0.1830 ± .0045 in. | ± 0.0113 in./ft |
| Total Potentiometer Resistance Tolerance | 0 |

**Error Due to Incorrect Total Potentiometer Resistance**

This error is eliminated through the use of an absolute zero reference voltage (ground). The potentiometer circuit is shown in Figure 27.

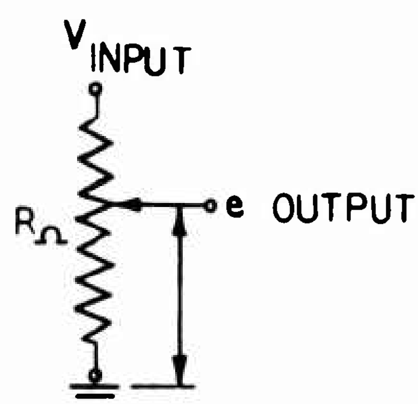



Figure 27. Potentiometer Circuit.

$V_{input}$ is the input voltage; $e_{output}$ is the output voltage. Since the wiper is geared directly to the cable length, $e_{output}$ is the fraction of $V_{input}$ that corresponds to the fraction of total cable length traveled. The value of $R_{\Omega}$ does not enter into this calculation; hence, the exact value of $R_{\Omega}$ is of no consequence.

Note: $R_{\Omega}$ would matter if we did not use operational amplifiers. If a bridge circuit were used to generate error signals, the error would be dependent on the total resistance of each leg of the bridge. Hence, the error would be sensitive to unmatched potentiometers. Since we use differential operational amplifiers, the error signal is dependent only on the fraction of total resistance and not on the resistance per se. Therefore, unmatched potentiometers have no effect on the error signal.

Errors Independent of Cable Travel

| Source | Error - 20-Ft System |
|---|---|
| Potentiometer Linearity Tolerance = ± .05% | ± .12 in. |
| Potentiometer Resolution Tolerance = $3600^{\circ}\ {}^{+5^{\circ}}_{-0^{\circ}}$ | ± .1656 in. |
| Flow-Divider Deadband = ± .8 ma | |
| Actual Feedback Gain Fore-Aft = 14 ma/ft | ± .93 in. |
| Actual Feedback Gain Pt-Stbd = 12 ma/ft | ± .80 in. |

$$\begin{aligned} \text{Total Error} &= \pm .0113 \text{ in./ft} + [\pm .12 \text{ in.} \pm .1656 \text{ in.} \pm .93 \text{ in.} \\ &\quad \pm .80 \text{ in.}] \\ &= \pm .0113 \text{ in./ft} + [\pm 2.0189 \text{ in.}] \end{aligned} \tag{25}$$

Cable Stretch Under Load

Cable stretch was measured during individual hoist tests and was found to be as follows:

$$\Delta \text{cable} = (1/20)(\text{wt}/63.5)$$

where

$$\Delta cable = \text{cable stretch, in.}$$
$$wt = \text{cable load, lb}$$
$$l = \text{length of cable payed out, ft}$$

This error is outside the feedback loop and must be added to the total inherent error.

Total Inherent Error

The system inherent error in terms of cable length differential,

$$\text{Total Inherent Error} = [\pm .0113/\text{ft} \pm 2.0189 + \Delta \text{cable}] \text{ (in.)} \qquad (26)$$

results in platform pitch and roll. Assuming a cable load differential of 50 lb and 20 ft of cable payed out, the total inherent difference between two cables would be as follows:

$$E_{inherent} = [\pm .0113(20) \pm 2.0189 + (20/20)(50/635) \text{ in.}] \qquad (27)$$

Assuming maximum cable length differentials, the resulting platform angles, from equation (19), would be as follows:

$$\theta p = \pm 2.58^{o}$$
$$\phi p = \pm 4.35^{o}$$

## STEADY STATE

As discussed in the analytical error analysis, the system is overdetermined; that is, the platform is suspended by four cables, while three would be sufficient. The practical result of this situation is that tests cannot be repeated. There is no unique solution; a range of data must be expected. For this reason, sufficient data were taken in three of the loading conditions to provide enough data for a statistical measure of the range of results. Figures 28, 29, and 30 show the range of results obtained in the pitch of the platform for loading condition 8. Two conclusions are drawn:

The arithmetic mean is a reliable measure of the most probable steady-state characteristic.

Sixty-five percent of all cases will fall within $\pm 1^{o}$ of the arithmetic mean of five or more samples.

The errors incurred during testing were compared with the errors predicted in the analytical analysis.

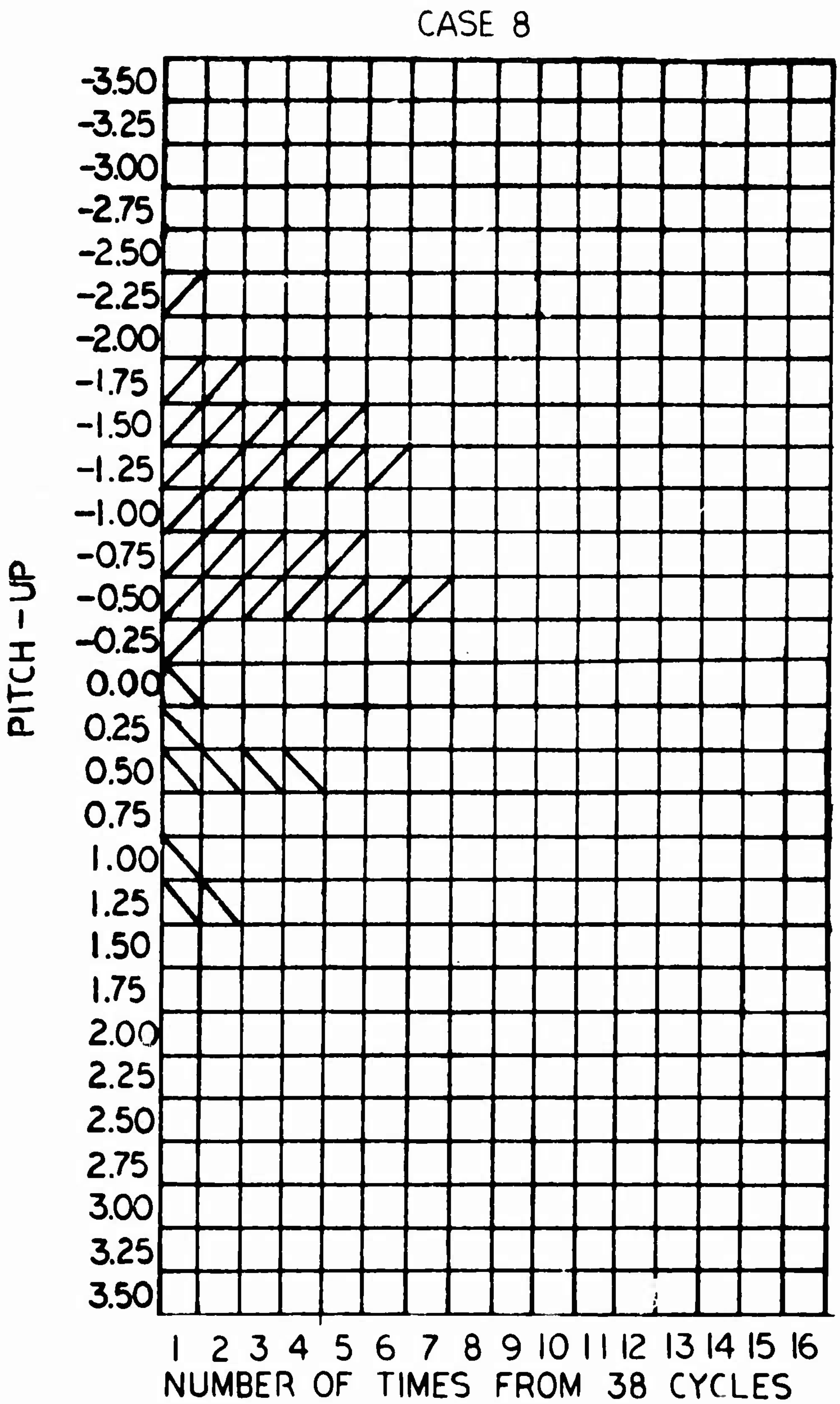



Figure 28. Change in Pitch Angle of Platform Going Up With 400-Lb Offset Load.

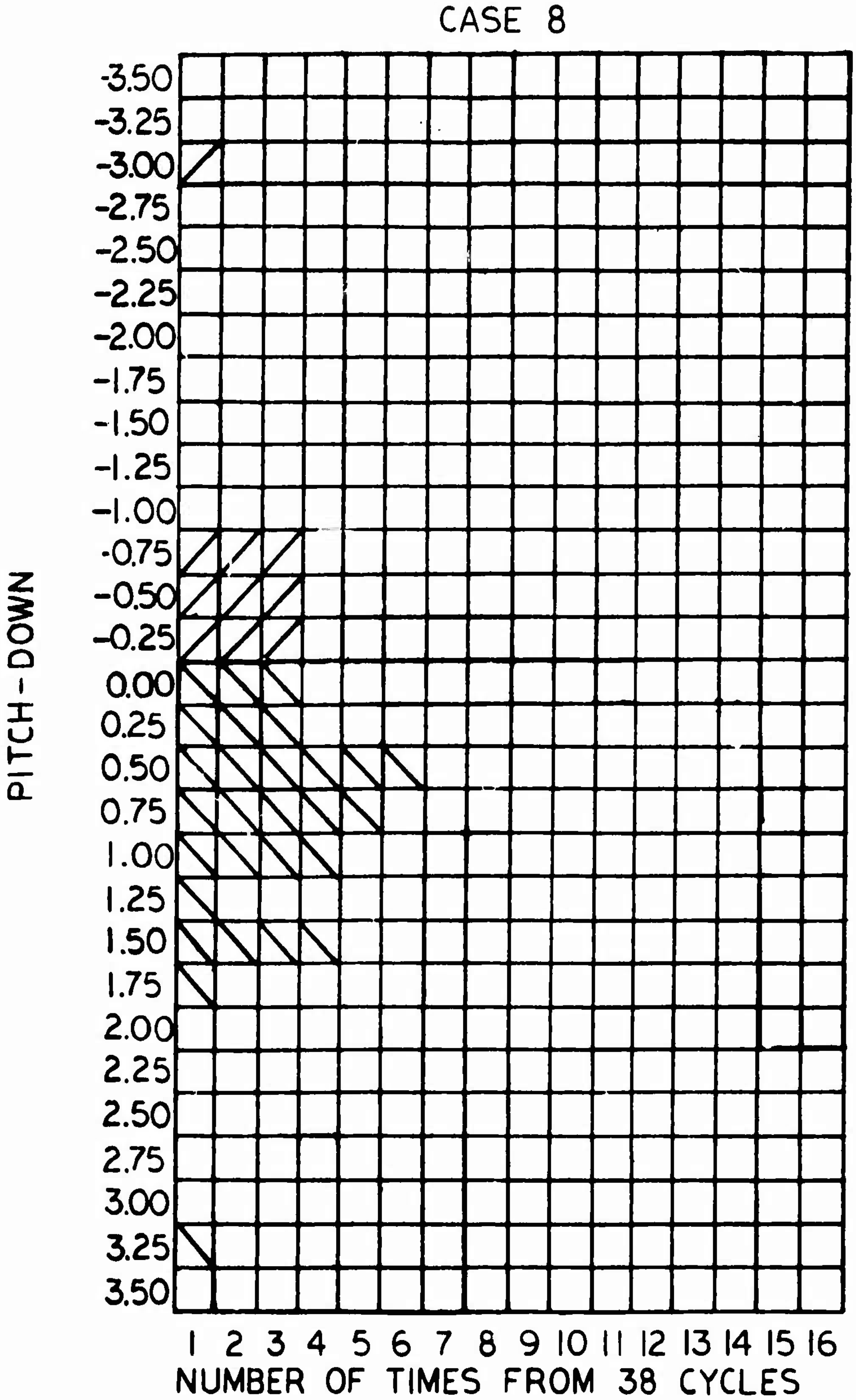



Figure 29. Change in Pitch Angle of Platform Going Down With 400-Lb Offset Load.

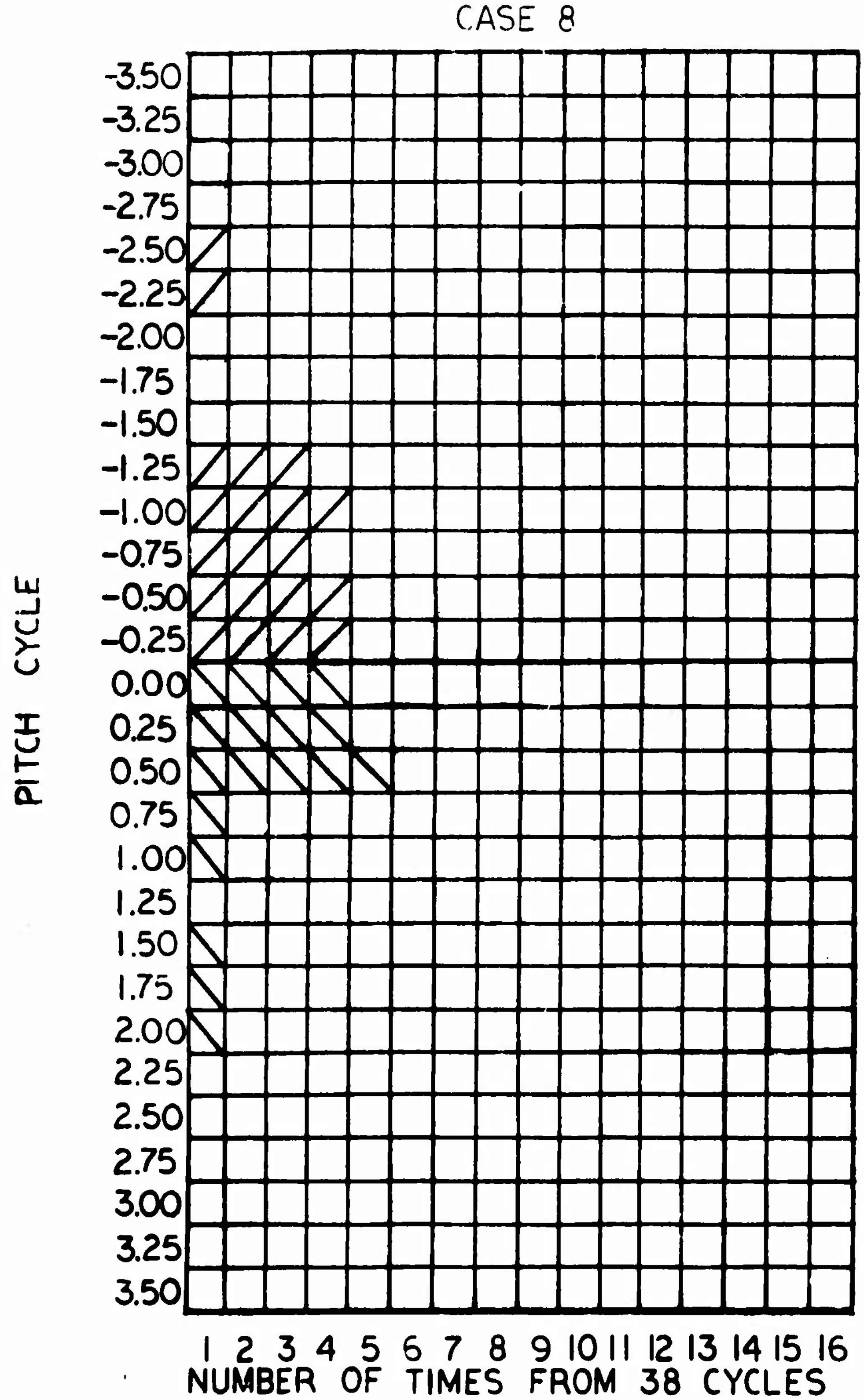



Figure 30. Change in Pitch Angle of Platform Complete Cycle With 400-Lb Offset Load.

Using the errors incurred during the ascension portion of the cycle with a constant load weight, the data can be compared to the loci of constant errors in pitch and roll angles of the platform, which were predicted by the analytical analysis and shown in Figure 21. In all cases, the data fall on or outside the contours, implying that Figure 21 is a reliable estimate of worst-case expectations for average changes from trim.

To determine whether or not the system is load sensitive, cases where the only variable was load weight shall be compared.

Data for Case 1 (no load on the patform) show that residual errors exist in the system which were larger than predicted. A comparison with Cases 6, 11, and 16 (centered loads of 200, 400, and 600, respectively) indicates that these errors are inherent in the system. This is true since errors decrease with loading, whereas errors due to the feedback system could only increase with loading. The suspected source of errors is overlap in the flow-divider spools, since the errors in Cases 1, 6, 11, and 16 are linearly distributed.

To determine whether or not the system is load position sensitive, cases where the only variable was the magnitude of the product of the distance from the center of the platform times the weight of the load shall be compared; this quantity shall be designated as Moment y or Moment x.

Data for Cases 2, 7, and 12 are compared. The respective quantities to be compared, Moment y, are as follows:

| Case | Moment y, in. -lb | Pitch, deg | | |
|---|---|---|---|---|
| | | Up | Down | Cycle |
| 2 | 6360 | -1.8 | 1.0 | -.8 |
| 7 | 7320 | -1.4 | 1.7 | .3 |
| 12 | 7800 | -3.7 | 1.8 | -1.9 |

If the system were sensitive to load position, pitching of the platform would be proportional to Moment y.

Similarly, Cases 4, 9, and 12 may be examined:

| Case | Moment x, in. -lb | Roll, deg | | |
|---|---|---|---|---|
| | | Up | Down | Cycle |
| 4 | 3620 | -3.6 | 2.7 | -.9 |
| 9 | 4160 | - .4 | .3 | -.1 |
| 14 | 4440 | -3.1 | -1.3 | -4.4 |

If the system were sensitive to load position, rolling of the platform would be proportional to Moment x.

Neither of the comparisons made above would substantiate the hypothesis that the system is sensitive to load position.

> Note: The pitch and roll quantitites stated above were case averages.

It may be noted that in all cases a bias seems to appear in the errors; that is, if a change of ($\alpha$) degrees is incurred during the ascension phase, a change of nearly ($-\alpha$) degrees is incurred during descent. This results in uniformly small errors during the cycle for all loading conditions. The source of bias is unclear, although an offset bias in the electrical power supply or the operational summing amplifiers would cause the effect. If this were the case, the error may easily be removed.

The inherent errors in the system, an inherent pitch error of $\pm 2.58^{\circ}$ and an inherent roll error of $\pm 4.35^{\circ}$, contribute significantly to the system error. These inherent errors must be considered when system accuracy is adjudged.

TRANSIENT ERRORS

Excellent correlation exists between predicted and empirical transient data.

Figure 26 shows the oscillograph recordings of differential cable lengths during the ascension of the platform with loading as in Case 7. This figure should be compared to Figure 18.

The following observations may be made from the transient data:

> The platform tends to twist during ascension. Oscillations may occur with highly offset or heavy loads.
>
> Oscillation amplitudes are approximately $\pm 1^{\circ}$. Amplitude of oscillations increases with load offset and weight.
>
> Frequency of oscillation is dependent on the ratio of feedback gain to distance between cables. As gain goes up and as distance between cables goes down, the frequency of the limit cycle oscillation* increases.

*A limit cycle oscillation is a nonlinear constant-amplitude oscillation. Amplitude does not tend to increase or decrease.

Figure 22 is modified in Figure 31 to show the dependence of amplitude of oscillation on load weight. The fact that the effect does not peak as predicted is explained by the inability of the hoists to operate at rated loads without slipping violently.

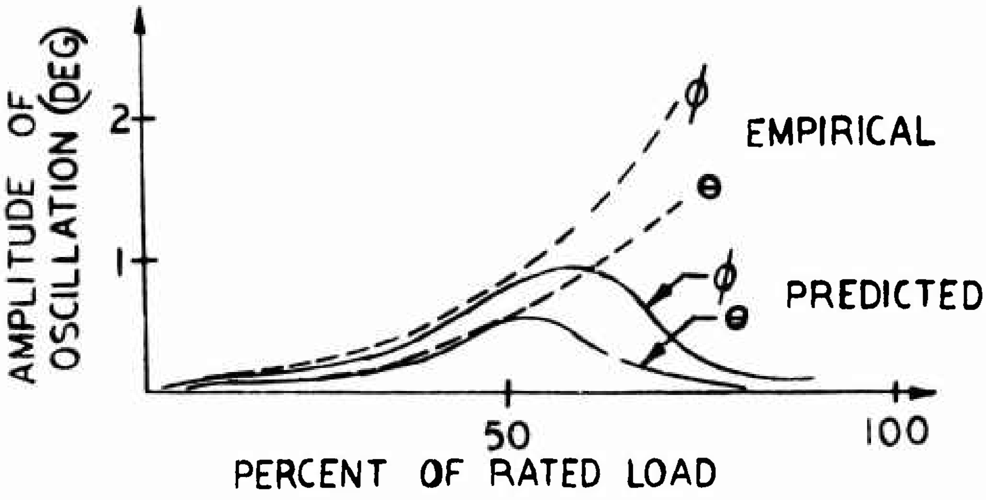



Figure 31. Comparison of Actual and Analytical Transient Response.

The effect of center-of-gravity offset on oscillation amplitude is unclear. It is obvious that the amplitude generally increases as the load is offset from the center of the platform, but the point where slippage obscures the predicted effect cannot be ascertained.

In no case did an oscillation exceed $\pm 3^{\circ}$ deviation from the empirical steady-state mean values.

## PROBLEM AREAS

### BOUNCE

Lack of system isolation resulted in acceleration loads that caused bouncing of the hoist load when a hoisting operation was started or stopped. This problem could easily be eliminated by incorporating a load isolation system.

### SLIPPAGE

A load brake system which ensures positive retention of a suspended load and smooth controllable lowering of the load is required as an integral part of a hoisting system.

The load brake incorporated in the rescue hoists is a Weston type; it is designed to intermittently slip and hold when lowering a load. Smooth lowering of loads will result when the slip and hold modes are indistinct. Failure of the hoist brakes to function properly caused spasmodic loading on the hoisting platform and on the hoists themselves. Hoist brakes must be improved to ensure desirable operating characteristics.

The load brake system incorporated in the CH-54A main hoist satisfies load retention and smooth load lowering requirements. This system employs a disk brake which is spring-loaded engaged when the system is shut off. When the operator actuates the system in the raise or lower mode, pressure in the hydraulic system releases the disk brake. A flow regulator valve in series with a relief valve prevents the load from "running away" when lowering. This type of system has proven to be effective and would eliminate the problems encountered with the Weston-type system.

### WAVERING AND ERROR

"Wavering" and "error" are terms applied to effects caused by the feedback control system. Wavering is the pitching and rolling of the platform that is caused by signals acting to level the platform. Error is the maximum change from the trim attitude that is caused by the loading condition. The amount of wavering permitted and the magnitude of the error encountered form a trade-off.

The parameters in the feedback system which have a significant effect on wavering and error are the amount of deadband in the flow dividers and the magnitude of feedback gains. The latter parameter was capable of being varied during the test. Since high feedback gains tend to excite wavering but to decrease error, and since low gains have the opposite effect, the magnitude of the gains was set at the threshold of wavering.

This setting yielded the least error possible with tolerable platform dynamic behavior.

If the dynamic behavior of the platform can be improved, then higher feedback gains could be employed, yielding a smaller system error. There are two techniques that will improve the dynamic characteristics. The first is to reduce or eliminate the deadband from the flow-divider valves. With the current flow dividers, a large error (and, significantly, a large rate of error) is built up before the feedback signal becomes effective. The second technique is to employ an additional feedback signal which uses rate-of-error information. This requires the use of tachometers as well as potentiometers, but the added damping should significantly improve dynamic behavior.

## OBSERVATIONS

Open-loop (no feedback) operation of the system dramatically shows the need for a synchronization system. With very light or slightly offset loads, the load-sensitive hoists would achieve $90^{\circ}$ (completely tipped) platform angles very rapidly.

Platform dynamics have a significant effect on system characteristics. The nonrigid platform induced and sustained oscillations during the hoisting operation.

Hoisting speeds can be significantly increased with a synchronization system.

Hoist performance was the limiting factor in the system, particularly performance of the hoist brakes. A load brake system which would be a significant improvement over the system employed in the rescue hoists and which would improve operating characteristics of the system is described in the previous section of this report.

There were numerous examples of a winch "bouncing" when the system was shut off. It is believed that this phenomenon is caused by flow across the flow-divider valves from one hydraulic line to another due to unequal pressure levels developed in the lines when the system is operating. "Bouncing" could be eliminated by installing isolation valves at hoist inlets.

## CONCLUSIONS

Operation of a four-point hoisting system is enhanced through the use of a feedback synchronization system. Open-loop operation of the system demonstrated the need for synchronization of the system. Without feedback, the multipoint system would have to be repeatedly stopped and leveled with the beeping controls. This is an unwieldy, time-consuming process.

The conclusions of the analytical error analysis are valid, and the analysis can be used as a basis for predicting performance of analogous systems.

The feedback circuit used in the model circuit operated successfully, and a similar system could be used in an aircraft application.

A synchronized multipoint hoisting system would permit higher hoisting speeds and would significantly increase the cargo handling potential of a multipoint hoist helicopter cargo handling system.

Accuracy of an electrohydraulic hoist synchronization system would increase measurably if the cumulative tolerances of the feedback system components were reduced. In particular, the reduction of the deadband and an improved flow gain characteristic of the flow-divider valve would be very desirable.

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## APPENDIX

## SYSTEM EVALUATION TEST DATA

**TABLE IV. CABLE LENGTH DIFFERENTIALS**

| Case | Cycle | Cables (1-2)* Up (in.) | Cables (1-2)* Down (in.) | Cables (1-2)* Cycle (in.) | Cables (2-4)* Up (in.) | Cables (2-4)* Down (in.) | Cables (2-4)* Cycle (in.) | Cables (3-4)* Up (in.) | Cables (3-4)* Down (in.) | Cables (3-4)* Cycle (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | -4.3 | 4.0 | -.4 | 3.2 | -4.0 | -.7 | 8.3 | .5 | 8.8 |
| | 2 | -4.1 | 3.1 | -1.1 | 4.0 | -4.0 | .0 | .0 | .5 | .5 |
| | 3 | -4.9 | 4.5 | -.4 | 3.8 | -4.3 | -.5 | 5.6 | .4 | 5.9 |
| | 4 | -5.0 | 4.7 | -.4 | 4.0 | -1.6 | 2.3 | 2.3 | -1.8 | .5 |
| | 5 | -4.1 | 4.5 | .4 | 2.2 | -1.8 | .4 | .4 | .0 | .4 |
| 1 Average of 5 cycles | | -4.5 | 4.1 | -.4 | 3.4 | -3.1 | .3 | 3.3 | -.1 | 3.2 |
| 2 | 1 | -4.7 | 2.9 | -1.8 | -5.0 | 1.1 | -4.0 | .4 | -1.6 | -1.3 |
| | 2 | -2.7 | 3.4 | .7 | 1.3 | .5 | -.7 | 1.1 | -1.4 | -.4 |
| | 3 | -3.1 | 3.4 | .4 | -.9 | 2.0 | 1.1 | 2.3 | -1.8 | .5 |
| | 4 | -3.4 | 3.4 | .0 | -1.6 | 1.3 | -.4 | 1.3 | -1.4 | -.2 |
| | 5 | -3.8 | 2.2 | -1.6 | -1.8 | .4 | -1.4 | .5 | -.5 | .0 |
| 2 Average of 5 cycles | | -3.5 | 3.1 | -.5 | -2.1 | 1.0 | -1.1 | 1.1 | -1.4 | -.3 |
| 3 | 1 | -2.2 | 2.3 | .2 | -3.4 | 2.3 | -1.1 | -.5 | -.5 | -1.1 |
| | 2 | -.7 | 2.0 | 1.3 | .7 | .4 | 1.1 | 2.0 | 1.1 | 3.1 |
| | 3 | -3.8 | 2.7 | -1.1 | 1.4 | -.9 | .5 | -3.8 | 5.0 | 1.3 |
| | 4 | -.7 | .7 | .0 | .2 | -1.3 | -1.1 | -.2 | -1.3 | -1.4 |
| | 5 | -2.2 | 4.0 | 1.8 | 1.3 | -.5 | .7 | -2.2 | 2.0 | -.2 |
| | 6 | -5.6 | 3.1 | -2.5 | .2 | -.9 | -.7 | -1.8 | .5 | -1.3 |
| | 7 | -.7 | 1.3 | .5 | 2.3 | -1.6 | .7 | .0 | .5 | .5 |
| | 8 | -2.9 | 5.9 | 3.1 | 1.6 | .5 | 2.2 | -2.0 | 6.8 | 4.9 |
| | 9 | -4.1 | 3.8 | -.4 | -2.5 | -1.6 | -4.1 | -2.9 | -3.4 | -6.3 |
| | 10 | -5.4 | 2.0 | -3.4 | 3.2 | -3.4 | -.2 | .0 | 2.2 | 2.2 |
| | 11 | -.5 | -.2 | -.7 | 4.5 | -5.0 | -.5 | -.4 | .0 | -.4 |
| | 12 | 2.3 | .2 | 2.5 | 4.7 | -3.2 | 1.4 | .4 | -.4 | .0 |
| | 13 | -2.5 | 5.4 | 2.9 | 2.7 | .2 | 2.9 | .0 | 3.1 | 3.1 |
| | 14 | -6.7 | 3.8 | -2.9 | .4 | -1.6 | -1.3 | -5.4 | 5.2 | -.2 |
| | 15 | -2.5 | 3.6 | 1.1 | -4.0 | 4.0 | .0 | .5 | .4 | .9 |
| | 16 | -4.5 | 4.5 | .0 | .5 | .2 | .7 | -.7 | -.9 | -1.6 |
| | 17 | -4.0 | 3.6 | -.4 | .2 | .0 | .2 | .9 | .4 | 1.3 |
| | 18 | -4.5 | 4.0 | -.5 | -1.4 | 1.3 | -.2 | -1.8 | 1.1 | -.7 |
| | 19 | -2.7 | .5 | -2.2 | -.4 | -1.8 | -2.2 | .4 | .0 | .4 |
| | 20 | -1.6 | 5.8 | 4.1 | 1.3 | 1.1 | 2.3 | -.2 | 1.1 | .9 |
| | 21 | -6.8 | 3.9 | -2.9 | 4.9 | -.4 | 4.5 | -3.2 | 2.2 | -1.1 |
| | 22 | -2.5 | 4.0 | 1.4 | -.9 | 2.3 | 1.4 | 2.5 | -1.8 | .7 |
| | 23 | -3.6 | 4.7 | 1.1 | -.7 | .7 | .0 | 1.1 | -1.3 | -.2 |

*Positive sign denotes that (1) is longer than (2), (2) is longer than (4), and (3) is longer than (4).

**TABLE IV - Continued**

| Case | Cycle | Cables (1-2) Up (in.) | Cables (1-2) Down (in.) | Cables (1-2) Cycle (in.) | Cables (2-4) Up (in.) | Cables (2-4) Down (in.) | Cables (2-4) Cycle (in.) | Cables (3-4) Up (in.) | Cables (3-4) Down (in.) | Cables (3-4) Cycle (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 24 | -5.0 | 4.3 | -.7 | -.7 | .7 | .0 | 1.1 | -2.0 | -.9 |
| | 25 | -4.1 | 1.6 | -2.5 | -2.5 | 1.3 | -1.3 | 2.9 | -2.0 | .9 |
| | 26 | -2.3 | 4.5 | 2.2 | 1.1 | .2 | 1.3 | -1.3 | 1.1 | -.2 |
| | 27 | -5.8 | 4.5 | -1.3 | -.9 | .0 | -.9 | -1.4 | 1.6 | .2 |
| | 28 | -3.2 | 2.3 | -.9 | -1.4 | 1.1 | -.4 | 2.0 | -1.6 | .4 |
| | 29 | -4.1 | 3.6 | -.5 | .7 | -.9 | -.2 | -3.1 | 2.3 | -.7 |
| | 30 | -.7 | 3.1 | 2.3 | 2.0 | -1.6 | .4 | -.9 | .9 | .0 |
| | 31 | -4.5 | 2.9 | -1.6 | -.7 | .7 | .0 | 1.3 | -.9 | .4 |
| | 32 | -3.8 | 3.6 | -.2 | -1.3 | 1.1 | -.2 | 1.6 | -1.8 | -.2 |
| | 33 | -2.7 | 3.2 | .5 | 2.0 | -.9 | 1.1 | -2.0 | 1.8 | -.2 |
| | 34 | -4.1 | 5.9 | 1.8 | -.5 | .9 | .4 | -1.8 | 2.0 | .2 |
| | 35 | -5.0 | 5.4 | .4 | -2.3 | 2.5 | .2 | .9 | .0 | .9 |
| | 36 | -6.1 | 6.5 | .4 | -.2 | .9 | .7 | -3.6 | 2.9 | -.7 |
| | 37 | -5.4 | 2.5 | -2.9 | -1.1 | -.9 | -2.0 | -.4 | 1.1 | .7 |
| | 38 | -3.8 | 5.9 | 2.2 | -1.8 | 2.7 | .9 | .5 | -.2 | .4 |
| | 39 | -3.1 | .2 | -2.9 | -2.0 | .5 | -1.4 | .9 | -1.4 | -.5 |
| | 40 | -2.3 | 2.3 | .0 | 1.4 | -1.1 | .4 | -2.7 | 2.9 | .2 |
| 3 Average of 40 cycles | | -3.4 | 3.3 | -.0 | .2 | -.1 | .2 | -.6 | .7 | .1 |
| 4 | 1 | -4.7 | 5.6 | .9 | 1.1 | -.7 | .4 | -2.7 | 2.5 | -.2 |
| | 2 | -5.4 | 4.9 | -.5 | 1.1 | -1.6 | -.5 | -2.7 | 3.2 | .5 |
| | 3 | -4.0 | 2.5 | -1.4 | .2 | -.4 | -.2 | 2.0 | -.7 | 1.3 |
| | 4 | -3.1 | 4.1 | 1.1 | 1.6 | -1.6 | .0 | -5.2 | 3.2 | -2.0 |
| | 5 | -12.1 | 1.4 | -10.6 | 1.8 | -1.4 | .4 | -1.3 | 2.2 | .9 |
| 4 Average of 5 cycles | | -5.8 | 3.7 | -2.1 | 1.2 | -1.2 | .0 | -2.0 | 2.1 | .1 |
| 5 | 1 | -7.0 | 2.2 | -4.9 | -4.1 | -3.4 | -7.6 | -7.4 | 6.3 | -1.1 |
| | 2 | -.5 | .4 | -.2 | 1.1 | -.9 | .2 | -2.5 | -1.3 | -3.8 |
| | 3 | .7 | .0 | .7 | .2 | 1.8 | 2.0 | 2.0 | 3.2 | 5.2 |
| | 4 | -2.0 | .5 | -1.4 | -1.3 | -.5 | -1.8 | -5.0 | -2.3 | -7.4 |
| | 5 | 1.4 | -2.2 | -.7 | 1.3 | -.9 | .4 | 3.8 | 2.2 | 5.9 |
| 5 Average of 5 cycles | | -1.5 | .2 | -1.3 | -.6 | -.8 | -1.4 | -1.8 | 1.6 | -.2 |
| 6 | 1 | .9 | 1.3 | 2.2 | -1.1 | 2.0 | .9 | .7 | -1.3 | -.5 |
| | 2 | -1.4 | 1.3 | -.2 | -2.0 | 1.6 | -.4 | 1.8 | -1.6 | .2 |
| | 3 | -1.6 | 2.7 | 1.1 | -1.6 | 1.3 | -.4 | 1.8 | -2.5 | -.7 |
| | 4 | -1.6 | .0 | -1.6 | -.9 | .9 | .0 | 2.2 | -1.1 | 1.1 |
| | 5 | .2 | .0 | .2 | -.7 | .4 | -.4 | 1.6 | -1.4 | .2 |

| | | Cables (1-2) | | | Cables (2-4) | | | Cables (3-4) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Case | Cycle | Up (in.) | Down (in.) | Cycle (in.) | Up (in.) | Down (in.) | Cycle (in.) | Up (in.) | Down (in.) | Cycle (in.) |
| 6 Average of 5 cycles | | -.7 | 1.0 | .3 | -1.3 | 1.2 | -.0 | 1.6 | -1.6 | .0 |
| 7 | 1 | .2 | .2 | .4 | -3.6 | 2.5 | -1.1 | .5 | -3.1 | -2.5 |
| | 2 | -2.0 | 4.7 | 2.7 | -3.2 | 5.2 | 2.0 | 2.7 | -.7 | 2.0 |
| | 3 | -.5 | 1.6 | 1.1 | -4.5 | 4.3 | -.2 | 1.4 | -1.4 | .0 |
| | 4 | -4.0 | 2.2 | -1.8 | 3.4 | -4.1 | -.7 | .5 | -.5 | .0 |
| | 5 | -2.5 | 3.6 | 1.1 | -3.1 | 3.8 | .7 | .4 | .0 | .4 |
| 7 Average of 5 cycles | | -1.8 | 2.4 | .7 | -2.2 | 2.3 | .1 | 1.1 | -1.2 | -.0 |
| 8 | 1 | -4.9 | 4.1 | -.7 | -1.4 | .9 | -.5 | -5.0 | 5.2 | .2 |
| | 2 | -2.3 | .5 | -1.8 | -.9 | .0 | -.9 | 1.1 | -2.9 | -1.8 |
| | 3 | -6.7 | 2.3 | -4.3 | -.4 | .5 | .2 | -2.9 | 3.1 | .2 |
| | 4 | -2.3 | 2.9 | .5 | -.4 | .7 | .4 | -4.1 | 4.0 | -.2 |
| | 5 | -2.3 | 1.4 | -.9 | -.7 | .0 | -.7 | -2.3 | 2.0 | -.4 |
| | 6 | -1.8 | 3.2 | 1.4 | .7 | -.4 | .4 | -4.5 | 5.2 | .7 |
| | 7 | -2.2 | 3.2 | 1.1 | .5 | .2 | .7 | -4.7 | 4.7 | .0 |
| | 8 | -3.2 | 3.6 | .4 | -.2 | .5 | .4 | -5.2 | 5.6 | .4 |
| | 9 | -5.0 | 4.7 | -.4 | -1.3 | .9 | -.4 | -5.4 | 5.0 | -.4 |
| | 10 | -2.9 | .5 | -2.3 | -2.3 | 1.6 | -.7 | -2.0 | 2.0 | .0 |
| | 11 | -1.4 | 2.2 | .7 | -2.8 | 1.8 | -.2 | -1.1 | 1.6 | .5 |
| | 12 | -2.0 | 2.7 | .7 | -.2 | -5.2 | -5.4 | -3.8 | 2.9 | -.9 |
| | 13 | -2.5 | .7 | -1.8 | -1.1 | .2 | -.9 | -3.1 | 3.1 | .0 |
| | 14 | -3.2 | 2.9 | -.4 | 1.6 | -1.8 | -.2 | -2.0 | 2.0 | .0 |
| | 15 | -3.1 | 2.5 | -.5 | -1.6 | 1.6 | .0 | -1.8 | 2.2 | .4 |
| | 16 | -2.7 | 3.1 | .4 | -2.2 | 1.1 | -1.1 | -3.1 | 4.0 | .9 |
| | 17 | -1.4 | .9 | -.5 | -1.8 | 2.0 | .2 | -3.1 | 2.2 | -.9 |
| | 18 | -1.8 | 1.4 | -.4 | -1.8 | 1.1 | -.7 | -1.8 | 2.5 | .7 |
| | 19 | -1.6 | 4.7 | 3.1 | -.5 | 2.2 | 1.6 | -3.6 | 3.8 | .2 |
| | 20 | -4.7 | 5.0 | .4 | -1.4 | 1.4 | .0 | -4.9 | 4.1 | -.7 |
| | 21 | -3.2 | 2.0 | -1.3 | -1.8 | 1.3 | -.5 | -2.3 | 2.9 | .5 |
| | 22 | -2.9 | 3.6 | .7 | -2.0 | 2.2 | .2 | -2.0 | 2.0 | .0 |
| | 23 | -3.8 | 3.4 | -.4 | -1.1 | .9 | -.2 | -5.0 | 5.0 | .0 |
| | 24 | -2.0 | .7 | -1.3 | -.9 | 1.6 | .7 | -4.0 | 4.0 | .0 |
| | 25 | -2.2 | 2.2 | .0 | -2.5 | 1.6 | -.9 | -2.2 | 2.3 | .2 |
| | 26 | -2.7 | .7 | -2.0 | -1.4 | .4 | -1.1 | -3.8 | 3.6 | -.2 |
| | 27 | .0 | 3.2 | 3.2 | -3.4 | 4.5 | 1.1 | -.7 | .9 | .2 |
| | 28 | -2.3 | 3.1 | .7 | -1.8 | 2.3 | .5 | -2.0 | 2.7 | .7 |
| | 29 | -4.7 | 4.0 | -.7 | -2.2 | 2.3 | .2 | -4.1 | 3.4 | -.7 |
| | 30 | -3.8 | 4.0 | .2 | -1.6 | 1.4 | -.2 | -4.7 | 4.7 | .0 |
| | 31 | -2.9 | -1.3 | -4.1 | [illegible] | -1.1 | -2.3 | 2.5 | -3.2 | -.7 |
| | 32 | 1.3 | 2.5 | 3.8 | .4 | 1.6 | 2.0 | -2.5 | 3.8 | 1.3 |
| | 33 | -4.3 | 2.5 | -1.8 | -2.5 | 1.6 | -.9 | -3.6 | 3.1 | -.5 |
| | 34 | -.9 | 3.2 | 2.3 | -1.6 | 2.7 | 1.1 | -3.1 | 3.8 | .7 |

| | | Cables (1-2) | | | Cables (2-4) | | | Cables (3-4) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Up | Down | Cycle | Up | Down | Cycle | Up | Down | Cycle |
| Case | Cycle | (in.) | (in.) | (in.) | (in.) | (in.) | (in.) | (in.) | (in.) | (in.) |
| 8 | 35 | -3.4 | .2 | -3.2 | -1.6 | 1.6 | .0 | -5.0 | 4.1 | -.9 |
| | 36 | .4 | 1.4 | 1.8 | -2.3 | 1.8 | -.5 | -2.0 | 2.5 | .5 |
| | 37 | -2.9 | 3.2 | .4 | -1.4 | 1.8 | .4 | -4.1 | 4.5 | .4 |
| | 38 | -2.3 | .2 | -2.2 | -2.2 | .7 | -1.4 | -3.8 | 3.1 | -.7 |
| 8 Average of 38 cycles | | -2.7 | 2.4 | -.2 | -1.3 | 1.0 | -.3 | -3.0 | 3.0 | -.0 |
| 9 | 1 | -2.0 | -.4 | -2.3 | 3.4 | -5.2 | -1.8 | -1.1 | -.4 | -1.4 |
| | 2 | -.4 | -.4 | -.7 | 4.3 | -4.5 | -.2 | -.2 | 1.4 | 1.3 |
| | 3 | 1.4 | .0 | 1.4 | 2.7 | -2.7 | .0 | 1.6 | -.7 | .9 |
| | 4 | -2.2 | 1.1 | -1.1 | 2.2 | -1.8 | .4 | .0 | .9 | .9 |
| | 5 | .9 | -.7 | .2 | 4.7 | -4.5 | .2 | -2.7 | 2.7 | .0 |
| 9 Average of 5 cycles | | -.4 | -.1 | -.5 | 3.5 | -3.7 | -.3 | -.5 | .8 | .3 |
| 10 | 1 | -1.4 | 4.3 | 2.9 | -5.9 | 2.3 | -3.6 | 3.8 | -2.5 | 1.3 |
| | 2 | -2.5 | 1.3 | -1.3 | -7.6 | 4.0 | -3.6 | 5.2 | -6.1 | -.9 |
| | 3 | -1.6 | 2.2 | .5 | -2.2 | 1.8 | -.4 | 7.9 | -7.7 | .2 |
| | 4 | -.4 | -.4 | -.7 | -9.0 | 6.5 | -2.5 | 6.5 | -.9 | 5.6 |
| | 5 | .7 | -2.0 | -1.3 | -.4 | 3.2 | 2.9 | 2.9 | -10.6 | -7.7 |
| 10 Average of 5 cycles | | -1.0 | 1.1 | .0 | -5.0 | 3.6 | -1.4 | 5.3 | -5.6 | -.3 |
| 11 | 1 | 2.7 | .4 | 3.1 | -1.3 | 1.3 | .0 | 2.7 | -3.1 | -.4 |
| | 2 | -.2 | -.7 | -.9 | -1.3 | 1.4 | .2 | 3.4 | -2.7 | .7 |
| | 3 | .9 | -.9 | .0 | -1.4 | 1.4 | .0 | 2.7 | -2.9 | -.2 |
| | 4 | .5 | -.2 | .4 | -1.4 | 1.4 | .0 | 2.2 | -2.2 | .0 |
| | 5 | .5 | -.9 | -.4 | -1.3 | .4 | -.9 | 2.9 | -1.8 | 1.1 |
| 11 Average of 5 cycles | | .9 | -.5 | .4 | -1.3 | 1.2 | -.1 | 2.8 | -2.5 | .3 |
| 12 | 1 | -.5 | .0 | -.5 | -7.4 | 5.0 | -2.3 | .2 | -.9 | -.7 |
| | 2 | -.4 | -.9 | -1.3 | -6.1 | 4.7 | -1.4 | 1.4 | -2.2 | -.7 |
| | 3 | -.7 | -.5 | -1.3 | -6.8 | 6.3 | -.5 | .7 | -1.8 | -1.1 |
| | 4 | .4 | -1.3 | -.9 | -5.4 | 2.2 | -3.2 | 1.4 | -1.4 | .0 |
| | 5 | -3.1 | -1.8 | -4.9 | -6.8 | 3.2 | -3.6 | -1.3 | .0 | -1.3 |
| 12 Average of 5 cycles | | -.9 | -.9 | -1.8 | -6.5 | 4.3 | -2.2 | .5 | -1.3 | -.8 |

Table title: TABLE IV - Continued

TABLE IV - Continued

| Case | Cycle | Cables (1-2) Up (in.) | Cables (1-2) Down (in.) | Cables (1-2) Cycle (in.) | Cables (2-4) Up (in.) | Cables (2-4) Down (in.) | Cables (2-4) Cycle (in.) | Cables (3-4) Up (in.) | Cables (3-4) Down (in.) | Cables (3-4) Cycle (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 1 | -.5 | .2 | -.4 | .5 | .7 | 1.3 | .5 | 1.3 | 1.6 |
| | 2 | -.5 | 1.8 | 1.3 | -.4 | 1.3 | .9 | -2.0 | 5.6 | 3.6 |
| | 3 | .0 | 1.6 | 1.6 | -1.1 | 1.4 | .4 | -4.5 | 4.5 | .0 |
| | 4 | -3.2 | 3.8 | .5 | -1.8 | 2.7 | 1.3 | -6.5 | 6.8 | .4 |
| | 5 | -1.8 | 3.4 | 1.6 | -3.8 | 4.5 | .7 | -4.0 | 5.6 | 1.6 |
| | 6 | -4.1 | .9 | -3.2 | -4.7 | 1.1 | -3.6 | -5.9 | 2.7 | -3.2 |
| | 7 | -4.1 | -.5 | -4.7 | -4.1 | 1.6 | -2.5 | -3.2 | 2.5 | -.7 |
| | 8 | -1.4 | .2 | -1.3 | .0 | -2.0 | -2.0 | -5.8 | 4.7 | -1.1 |
| | 9 | 1.4 | 1.3 | 2.7 | 1.8 | 1.3 | 3.1 | -4.1 | 6.5 | 2.3 |
| | 10 | -1.4 | -.7 | -2.2 | -1.3 | -.4 | -1.6 | -7.6 | 2.9 | -4.7 |
| | 11 | -1.8 | 1.4 | -.4 | -.9 | .7 | -.2 | -2.9 | 4.0 | 1.1 |
| | 12 | -.4 | 2.7 | 2.3 | -1.1 | 2.3 | 1.3 | -4.0 | 4.9 | .9 |
| | 13 | -2.9 | 3.2 | .4 | -1.8 | 1.8 | .0 | -4.0 | 5.6 | 1.6 |
| | 14 | -1.8 | -.4 | -2.2 | -1.6 | .9 | -.7 | -4.9 | 4.7 | -.2 |
| | 15 | -1.4 | .4 | -1.1 | -1.6 | 1.1 | -.5 | -6.8 | 5.2 | -1.6 |
| | 16 | 1.4 | 2.9 | 4.3 | -1.1 | .7 | -.4 | -2.5 | 5.0 | 2.5 |
| | 17 | -1.4 | 2.2 | .7 | 3.6 | -.5 | 3.1 | -4.9 | 5.8 | .9 |
| | 18 | .2 | .7 | .9 | -.2 | .5 | .4 | -3.1 | 2.5 | -.5 |
| | 19 | .5 | 2.2 | 2.7 | -.9 | 5.0 | 4.1 | -1.6 | 4.5 | 2.9 |
| | 20 | -4.3 | -.9 | -5.2 | -4.5 | .0 | -4.5 | -5.9 | 2.2 | -3.8 |
| | 21 | 2.0 | 2.0 | 4.0 | -.5 | 4.5 | 4.0 | -1.3 | -.2 | -1.4 |
| | 22 | .0 | 4.1 | 4.1 | -.2 | 1.8 | 1.6 | -.9 | 2.9 | 2.0 |
| | 23 | -3.4 | -.5 | -4.0 | -3.6 | 3.1 | -.5 | -.4 | 1.3 | .9 |
| | 24 | .4 | .9 | 1.3 | -.7 | .0 | -.7 | -3.4 | 1.3 | -2.2 |
| | 25 | -2.3 | 1.4 | -.9 | .0 | .7 | .7 | -2.0 | 4.3 | 2.3 |
| | 26 | -.4 | .5 | .2 | -2.9 | 2.7 | -.2 | -4.3 | 2.5 | -1.8 |
| | 27 | -1.3 | 4.1 | 2.9 | -3.1 | 4.3 | 1.3 | -2.7 | 6.1 | 3.4 |
| | 28 | -6.7 | 3.4 | -3.2 | -4.7 | 4.9 | .2 | -4.5 | 1.6 | -2.9 |
| | 29 | -6.5 | 3.8 | -2.7 | -5.6 | 4.1 | -1.4 | -3.6 | 5.8 | 2.2 |
| | 30 | -2.7 | -1.1 | -3.8 | -3.8 | 4.5 | .7 | -4.5 | -3.1 | -7.6 |
| | 31 | -.7 | .5 | -.2 | -4.1 | -.9 | -5.0 | 1.3 | .5 | 1.8 |
| | 32 | -5.2 | 4.7 | -.5 | -2.5 | 2.3 | -.2 | -7.9 | 8.3 | .4 |
| | 33 | -6.3 | -3.2 | -9.5 | -5.4 | -2.0 | -7.4 | -6.3 | -4.7 | -11.0 |
| | 34 | -5.4 | 2.5 | -2.9 | -4.5 | 2.3 | -2.2 | -8.1 | 4.0 | -4.1 |
| | 35 | -6.1 | -.9 | -7.0 | -5.4 | .4 | -5.0 | -3.8 | -.7 | -4.5 |
| | 36 | -2.3 | 1.6 | -.7 | -.1 | 1.1 | .0 | -5.2 | 5.0 | -.2 |
| | 37 | -2.3 | 1.3 | -1.1 | -1.6 | .4 | -1.3 | -5.0 | .7 | -4.3 |
| | 38 | -.5 | -3.8 | -4.3 | .0 | -1.4 | -1.4 | -5.2 | .0 | -5.2 |
| | 39 | -4.9 | 4.9 | .0 | -2.3 | 2.5 | .2 | -5.2 | 4.1 | -1.1 |
| | 40 | -6.8 | 1.8 | -5.0 | -2.3 | -.7 | -3.1 | -6.5 | 3.8 | -2.7 |
| 13 Average of 40 cycles | | -2.1 | 1.3 | -.8 | -1.0 | 1.4 | -.5 | -3.8 | 3.0 | -.7 |
| 14 | 1 | -5.8 | -2.9 | -.86 | 1.3 | -3.1 | -1.8 | -5.4 | 1.6 | -3.8 |
| | 2 | -3.2 | .7 | -2.5 | -.9 | .4 | -.5 | -3.4 | .7 | -2.7 |
| | 3 | -.4 | -.7 | -1.1 | 1.6 | -.7 | .9 | -3.6 | 2.0 | -1.6 |

**TABLE IV - Continued**

| Case | Cycle | Cables (1-2) Up (in.) | Cables (1-2) Down (in.) | Cables (1-2) Cycle (in.) | Cables (2-4) Up (in.) | Cables (2-4) Down (in.) | Cables (2-4) Cycle (in.) | Cables (3-4) Up (in.) | Cables (3-4) Down (in.) | Cables (3-4) Cycle (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 4 | -4.7 | -2.0 | -6.7 | .7 | -3.4 | -2.7 | -2.0 | .4 | -1.6 |
| | 5 | -.5 | -10.1 | -10.6 | 5.4 | -7.2 | -1.8 | -4.5 | -4.1 | -8.6 |
| 14 Average of 5 cycles | | -2.9 | -3.0 | -5.9 | 1.6 | -2.8 | -1.2 | -3.8 | .1 | -3.7 |
| 15 | 1 | -4.0 | -2.0 | -5.9 | -4.3 | 3.8 | -.5 | -6.8 | .7 | -6.1 |
| | 2 | -5.9 | -4.0 | -9.9 | -4.1 | -2.3 | -6.5 | -7.0 | -4.1 | -11.2 |
| | 3 | -8.3 | -2.3 | -10.6 | -6.5 | 1.4 | -5.0 | -10.8 | 1.3 | -9.5 |
| | 4 | -7.4 | 5.0 | -2.3 | -4.1 | 3.2 | -.9 | -10.3 | 12.1 | 1.8 |
| | 5 | -5.2 | 3.1 | -2.2 | -2.9 | .9 | -2.0 | -12.6 | 5.6 | -7.0 |
| 15 Average of 5 cycles | | -6.2 | -.0 | -6.2 | -4.4 | 1.4 | -3.0 | -9.5 | 3.1 | -6.4 |
| 16 | 1 | -.4 | -3.4 | -3.8 | -1.3 | 1.1 | -.2 | .5 | -2.3 | -1.8 |
| | 2 | 2.0 | -2.3 | -.4 | -.5 | .7 | .2 | 2.0 | -1.4 | .5 |
| | 3 | 2.5 | -3.2 | -.7 | -.4 | .2 | -.2 | 1.6 | -1.8 | -.2 |
| | 4 | 3.2 | -2.3 | .9 | -.2 | -.2 | -.4 | 1.4 | -2.9 | -1.4 |
| | 5 | 2.3 | -3.2 | -.9 | -.2 | .5 | .4 | 3.1 | -2.0 | 1.1 |
| 16 Average of 5 cycles | | 1.9 | -2.9 | -1.0 | -.5 | .5 | -.0 | 1.7 | -2.1 | -.4 |

| TABLE V. PLATFORM ANGLES | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Pitch | | | Roll | | |
| | | Up | Down | Cycle | Up | Down | Cycle |
| Case | Cycle | (deg) | (deg) | (deg) | (deg) | (deg) | (deg) |
| 1 | 1 | -1.7 | -1.2 | -2.9 | 1.8 | 2.1 | 3.9 |
| | 2 | 1.0 | -1.5 | -.4 | -1.9 | 1.[illegible] | -.3 |
| | 3 | -.8 | -1.2 | -2.0 | .3 | 2.3 | 2.6 |
| | 4 | .1 | .9 | 1.0 | -1.3 | 1.3 | .1 |
| | 5 | -.0 | .2 | .2 | -1.8 | 2.1 | .3 |
| 1 Average of 5 cycles | | -.3 | -.6 | -.8 | -.6 | 1.9 | 1.3 |
| 2 | 1 | -4.2 | 1.8 | -2.3 | -2.0 | .6 | -1.4 |
| | 2 | -1.7 | 1.6 | -.1 | -.8 | .9 | .2 |
| | 3 | -2.0 | 2.5 | .5 | -.3 | .8 | .1 |
| | 4 | -2.2 | 2.0 | -.1 | -1.0 | .9 | -.1 |
| | 5 | -2.2 | .9 | -1.2 | -1.5 | .8 | -.8 |
| 2 Average of 5 cycles | | -2.5 | 1.8 | -.7 | -1.1 | .8 | -.3 |
| 3 | 1 | -2.3 | 2.1 | -.2 | -1.3 | .8 | -.4 |
| | 2 | -.3 | .4 | .1 | .6 | 1.4 | 2.0 |
| | 3 | .8 | -1.1 | -.3 | -3.5 | 3.6 | .1 |
| | 4 | -.0 | -.2 | -.2 | -.4 | -.3 | -.7 |
| | 5 | .7 | .2 | 1.0 | -2.0 | 2.8 | .8 |
| | 6 | -.9 | .2 | -.7 | -3.4 | 1.7 | -1.8 |
| | 7 | 1.1 | -.7 | .4 | -.3 | .8 | .5 |
| | 8 | .6 | .0 | .7 | -2.3 | 5.9 | 3.7 |
| | 9 | -1.7 | 1.1 | -.6 | -3.3 | .2 | -3.1 |
| | 10 | .3 | -1.9 | -1.6 | -2.5 | 1.9 | -.6 |
| | 11 | 2.4 | -2.8 | -.4 | -.4 | -.1 | -.5 |
| | 12 | 3.1 | -1.6 | 1.5 | 1.3 | -.1 | 1.2 |
| | 13 | .8 | .7 | 1.5 | -1.2 | 3.9 | 2.8 |
| | 14 | -.1 | -1.3 | -1.4 | -5.6 | 4.2 | -1.4 |
| | 15 | -3.1 | 3.1 | .0 | -.9 | 1.8 | .9 |
| | 16 | -.7 | 1.6 | .8 | -2.4 | 1.7 | -.8 |
| | 17 | -1.2 | .9 | -.3 | -1.4 | 1.8 | .4 |
| | 18 | -1.5 | 1.5 | -.0 | -2.9 | 2.3 | -.6 |
| | 19 | -1.0 | -.8 | -1.9 | -1.1 | .3 | -.8 |
| | 20 | .3 | 1.9 | 2.2 | -.8 | 3.2 | 2.3 |
| | 21 | 1.7 | .3 | 2.0 | -4.7 | 2.8 | -1.9 |
| | 22 | -1.9 | 2.9 | 1.0 | .0 | 1.0 | 1.0 |
| | 23 | -1.7 | 2.0 | .3 | -1.2 | 1.6 | .4 |
| | 24 | -2.1 | 2.1 | .0 | -1.8 | 1.1 | -.8 |
| | 25 | -3.3 | 1.7 | -1.6 | -.6 | -.2 | -.8 |
| | 26 | .3 | 1.0 | 1.3 | -1.7 | 2.6 | .9 |
| | 27 | -1.7 | .8 | -.9 | -3.3 | 2.8 | -.5 |
| | 28 | -2.2 | 1.7 | -.5 | -.6 | .3 | -.3 |

**TABLE V - Continued**

| Case | Cycle | Pitch Up (deg) | Pitch Down (deg) | Pitch Cycle (deg) | Roll Up (deg) | Roll Down (deg) | Roll Cycle (deg) |
|---|---|---|---|---|---|---|---|
| 3 | 29 | .1 | -.1 | -.0 | -3.3 | 2.8 | -.6 |
| | 30 | 1.1 | -.3 | .8 | -.8 | 1.8 | 1.1 |
| | 31 | -2.0 | 1.4 | -.5 | -1.5 | .9 | -.6 |
| | 32 | -2.2 | 2.1 | -.1 | -1.0 | .8 | -.2 |
| | 33 | .9 | -.1 | .8 | -2.2 | 2.3 | .2 |
| | 34 | -.7 | 1.6 | .6 | -2.8 | 3.7 | .9 |
| | 35 | -2.9 | 2.9 | -.0 | -1.9 | 2.5 | .6 |
| | 36 | -.8 | 1.5 | .7 | -4.5 | 4.3 | -.2 |
| | 37 | -2.0 | -.1 | -2.1 | -2.7 | 1.7 | -1.0 |
| | 38 | -2.2 | 3.2 | 1.0 | -1.5 | 2.7 | 1.2 |
| | 39 | -2.2 | .7 | -1.4 | -1.0 | -.6 | -1.6 |
| | 40 | .9 | -.7 | .1 | -2.3 | 2.4 | .1 |
| 3 Average of 40 cycles | | -.7 | .7 | .0 | -1.8 | 1.9 | .1 |
| 4 | 1 | .0 | .4 | .5 | -3.2 | 3.6 | .3 |
| | 2 | -.1 | -.4 | -.6 | -3.8 | 3.3 | .0 |
| | 3 | -1.5 | .7 | -.8 | -.9 | .8 | -.1 |
| | 4 | 1.5 | -.6 | .8 | -3.8 | 3.4 | -.4 |
| | 5 | -2.0 | -1.0 | -3.0 | -6.2 | 1.[illegible] | -4.5 |
| 4 Average of 5 cycles | | -.4 | -.2 | -.6 | -3.6 | 2.7 | -.9 |
| 5 | 1 | -2.2 | -3.0 | -5.2 | -6.7 | 3.9 | -2.8 |
| | 2 | 1.1 | -.0 | 1.1 | -1.4 | -.4 | -1.8 |
| | 3 | -.2 | .1 | -.1 | 1.3 | 1.5 | 2.8 |
| | 4 | .1 | .5 | .6 | -3.3 | -.8 | -4.1 |
| | 5 | .0 | -1.7 | -1.6 | 2.4 | .0 | 2.4 |
| 5 Average of 5 cycles | | -.2 | -.8 | -1.[illegible] | -1.5 | .8 | -.7 |
| 6 | 1 | -.5 | 1.8 | 1.2 | .8 | -.0 | .8 |
| | 2 | -2.0 | 1.7 | -.3 | .2 | -.2 | .0 |
| | 3 | -1.8 | 2.1 | .3 | .1 | .1 | .2 |
| | 4 | -1.5 | .8 | -.7 | .3 | -.5 | -.3 |
| | 5 | -.8 | .6 | -.2 | .8 | -.7 | .2 |
| 6 Average of 5 cycles | | -1.3 | 1.4 | .1 | .4 | -.3 | .2 |

| | | Pitch | | | Roll | | |
|---|---|---|---|---|---|---|---|
| Case | Cycle | Up (deg) | Down (deg) | Cycle (deg) | Up (deg) | Down (deg) | Cycle (deg) |
| 7 | 1 | -2.1 | 2.3 | .2 | .3 | -1.3 | -1.0 |
| | 2 | -3.1 | 4.4 | 1.3 | .3 | 1.8 | 2.2 |
| | 3 | -3.0 | 3.2 | .2 | .4 | .1 | .5 |
| | 4 | .6 | -1.5 | -.9 | -1.6 | .8 | -.8 |
| | 5 | -2.5 | 3.1 | .6 | -1.0 | 1.7 | .7 |
| 7 Average of 5 Cycles | | -2.0 | 2.3 | .3 | -.3 | .6 | .3 |
| 8 | 1 | -.7 | .2 | -.5 | -4.6 | 4.3 | -.3 |
| | 2 | -1.4 | .9 | -.5 | -.6 | -1.1 | -1.7 |
| | 3 | -1.2 | .1 | -1.1 | -4.4 | 2.5 | -1.9 |
| | 4 | .3 | .1 | .4 | -3.0 | 3.2 | .2 |
| | 5 | -.4 | -.1 | -.5 | -2.2 | 1.6 | -.6 |
| | 6 | 1.1 | -.7 | .4 | -2.9 | 3.9 | 1.0 |
| | 7 | 1.0 | -.3 | .7 | -3.2 | 3.7 | .5 |
| | 8 | .4 | -.2 | .2 | -3.9 | 4.3 | .3 |
| | 9 | -.6 | .4 | -.2 | -4.8 | 4.5 | -.3 |
| | 10 | -1.5 | .5 | -1.0 | -2.3 | -.2 | -1.1 |
| | 11 | -1.2 | 1.1 | -.0 | -1.2 | 1.8 | .6 |
| | 12 | .4 | -2.9 | -2.5 | -2.7 | 2.6 | -.1 |
| | 13 | -.4 | -.6 | -1.0 | -2.6 | 1.8 | -.8 |
| | 14 | .5 | -.7 | -.2 | -2.4 | 2.3 | -.2 |
| | 15 | -1.2 | 1.0 | -.2 | -2.3 | 2.2 | -.1 |
| | 16 | -1.1 | .3 | -.7 | -2.7 | 3.3 | .6 |
| | 17 | -.5 | .7 | .2 | -2.1 | 1.4 | -.7 |
| | 18 | -1.0 | .3 | -.7 | -1.7 | 1.8 | .2 |
| | 19 | .2 | 1.4 | 1.7 | -2.4 | 3.9 | 1.5 |
| | 20 | -.7 | 1.0 | .3 | -4.4 | 4.3 | -.2 |
| | 21 | -1.2 | .4 | -.8 | -2.6 | 2.3 | -.3 |
| | 22 | -1.3 | 1.6 | .3 | -2.3 | 2.6 | .3 |
| | 23 | -.2 | .0 | -.2 | -4.1 | 3.9 | -.2 |
| | 24 | .0 | -.0 | .0 | -2.8 | 2.2 | -.6 |
| | 25 | -1.4 | .8 | -.5 | -2.0 | 2.1 | .1 |
| | 26 | -.5 | -.6 | -1.1 | -3.0 | 2.0 | -1.0 |
| | 27 | -1.7 | 3.1 | 1.4 | -.3 | 1.9 | 1.6 |
| | 28 | -1.1 | 1.4 | .3 | -2.0 | 2.7 | .7 |
| | 29 | -1.3 | 1.4 | .1 | -4.1 | 3.4 | -.7 |
| | 30 | -.6 | .6 | -.0 | -3.9 | 4.0 | .1 |
| | 31 | -2.2 | -.0 | -2.2 | -.2 | -2.1 | -2.3 |
| | 32 | 1.3 | .5 | 1.8 | -.6 | 2.9 | 2.3 |
| | 33 | -1.6 | .7 | -.8 | -3.7 | 2.6 | -1.1 |
| | 34 | -.3 | 1.3 | 1.0 | -1.8 | 3.3 | 1.4 |
| | 35 | -.8 | -.2 | -.6 | -3.9 | 2.0 | -1.9 |
| | 36 | -.4 | .7 | .0 | -.8 | 1.8 | 1.1 |
| | 37 | -.4 | .6 | .2 | -3.3 | 3.6 | .3 |
| | 38 | -.8 | -.4 | -1.2 | -2.8 | 1.5 | -1.3 |

| TABLE V - Continued | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Pitch | | | Roll | | |
| Case | Cycle | Up (deg) | Down (deg) | Cycle (deg) | Up (deg) | Down (deg) | Cycle (deg) |
| 8 Average of 38 cycles | | -.6 | .4 | -.2 | -2.6 | 2.5 | -.1 |
| 9 | 1 | 1.6 | -2.9 | -1.2 | -1.4 | -.3 | -1.8 |
| | 2 | 2.3 | -3.0 | -.6 | -.3 | .5 | .3 |
| | 3 | 1.4 | -1.3 | .1 | 1.4 | -.3 | 1.1 |
| | 4 | .6 | -.9 | -.3 | -1.0 | .9 | -.1 |
| | 5 | 3.6 | -3.4 | .1 | -.8 | .9 | .1 |
| 9 Average of 5 cycles | | 1.9 | -2.3 | -.4 | -.4 | .3 | -.1 |
| 10 | 1 | -4.7 | 3.2 | -1.5 | 1.1 | .8 | 1.9 |
| | 2 | -6.3 | 4.2 | -2.1 | 1.3 | -2.3 | -1.0 |
| | 3 | -3.8 | 3.7 | -.1 | 2.9 | -2.6 | .3 |
| | 4 | -6.9 | 3.7 | -3.1 | 2.8 | -.6 | 2.3 |
| | 5 | -.8 | 4.2 | 3.4 | 1.7 | -5.8 | -4.2 |
| 10 Average of 5 cycles | | -4.5 | 3.8 | -.7 | 2.0 | -2.1 | -.1 |
| 11 | 1 | -.7 | 1.6 | .9 | 2.5 | -1.3 | 1.3 |
| | 2 | -1.7 | 1.3 | -.3 | 1.5 | -1.6 | -.1 |
| | 3 | -1.3 | 1.3 | .0 | 1.7 | -1.8 | -.1 |
| | 4 | -1.2 | 1.3 | .1 | 1.3 | -1.1 | .2 |
| | 5 | -1.3 | .4 | -.9 | 1.6 | -1.3 | .3 |
| 11 Average of 5 cycles | | -1.3 | 1.2 | -.0 | 1.7 | -1.4 | .3 |
| 12 | 1 | -4.3 | 3.0 | -1.2 | -.2 | -.4 | -.6 |
| | 2 | -3.9 | 2.9 | -.9 | .5 | -1.4 | -.9 |
| | 3 | -4.2 | 3.8 | -.3 | .0 | -1.1 | -1.1 |
| | 4 | -3.3 | 1.2 | -2.0 | .8 | -1.3 | -.4 |
| | 5 | -4.3 | 1.3 | -3.0 | -2.0 | -.8 | -2.8 |
| 12 Average of 5 cycles | | -4.0 | 2.5 | -1.5 | -.2 | -1.0 | -1.2 |
| 13 | 1 | .0 | .1 | .1 | .0 | .7 | .7 |
| | 2 | .2 | -.3 | -.1 | -1.2 | 3.4 | 2.3 |
| | 3 | .6 | -.0 | .6 | -2.1 | 2.8 | .8 |
| | 4 | .1 | .6 | .7 | -4.5 | 4.9 | .4 |

| TABLE V - Continued | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Pitch | | | Roll | | |
| Case | Cycle | Up (deg) | Down (deg) | Cycle (deg) | Up (deg) | Down (deg) | Cycle (deg) |
| 13 | 5 | -1.5 | 1.9 | .4 | -2.7 | 4.2 | 1.5 |
| | 6 | -2.1 | .1 | -2.0 | -4.7 | 1.7 | -3.0 |
| | 7 | -2.5 | .0 | -2.5 | -3.4 | .9 | -2.5 |
| | 8 | 1.2 | -2.3 | -1.1 | -3.3 | 2.3 | -1.1 |
| | 9 | 2.5 | -.7 | 1.8 | -1.3 | 3.6 | 2.3 |
| | 10 | 1.0 | -1.2 | -.2 | -4.2 | 1.0 | -3.2 |
| | 11 | -.2 | -.3 | -.5 | -2.2 | 2.5 | .3 |
| | 12 | .4 | .7 | 1.1 | -2.0 | 3.5 | 1.5 |
| | 13 | -.7 | .3 | -.3 | -3.2 | 4.1 | .9 |
| | 14 | -.0 | -.9 | -.9 | -3.1 | 2.0 | -1.1 |
| | 15 | .6 | -.7 | -.1 | -3.8 | 2.6 | -1.3 |
| | 16 | .5 | -.2 | .3 | -.5 | 3.7 | 3.2 |
| | 17 | 2.9 | -1.3 | 1.6 | -2.9 | 3.7 | .8 |
| | 18 | .8 | -.2 | .6 | -1.3 | 1.5 | .2 |
| | 19 | .1 | 2.1 | 2.2 | -.5 | 3.1 | 2.6 |
| | 20 | -2.0 | -.8 | -2.9 | -4.8 | .6 | -4.2 |
| | 21 | .6 | 3.1 | 3.7 | .3 | .8 | 1.2 |
| | 22 | .1 | 1.3 | 1.5 | -.4 | 3.3 | 2.8 |
| | 23 | -2.8 | 1.2 | -1.6 | -1.8 | .3 | -1.4 |
| | 24 | .6 | -.1 | .5 | -1.4 | 1.0 | -.4 |
| | 25 | -.1 | -.4 | -.5 | -2.0 | 2.7 | .7 |
| | 26 | -.5 | .9 | .4 | -2.2 | 1.4 | -.8 |
| | 27 | -1.3 | 1.8 | .5 | -1.8 | 4.8 | 2.9 |
| | 28 | -3.2 | 3.2 | .0 | -5.2 | 2.3 | -2.8 |
| | 29 | -3.9 | 1.7 | -2.1 | -4.7 | 4.4 | -.3 |
| | 30 | -1.6 | 3.0 | 1.4 | -3.3 | -1.9 | -5.3 |
| | 31 | -2.8 | -.5 | -3.3 | .3 | .5 | .8 |
| | 32 | -.6 | .3 | -.3 | -6.1 | 6.0 | -.1 |
| | 33 | -3.0 | -.7 | -3.7 | -5.8 | -3.7 | -9.5 |
| | 34 | -1.7 | .9 | -.8 | -6.3 | 3.0 | -3.3 |
| | 35 | -3.6 | .1 | -3.5 | -4.6 | -.8 | -5.3 |
| | 36 | .2 | -.3 | -.1 | -3.5 | 3.1 | -.4 |
| | 37 | -.1 | .3 | .2 | -3.4 | .9 | -2.5 |
| | 38 | 1.3 | -1.8 | -.5 | -2.7 | -1.8 | -4.4 |
| | 39 | -1.2 | 1.6 | .4 | -4.7 | 4.2 | -.5 |
| | 40 | -1.4 | -.9 | -2.3 | -6.2 | 2.6 | -3.6 |
| **13 Average of 40 cycles** | | -.5 | .3 | -.3 | -2.7 | 2.0 | -.7 |
| 14 | 1 | .6 | -2.9 | -2.3 | -5.2 | -.6 | -5.8 |
| | 2 | -.4 | .2 | -.2 | -3.1 | .7 | -2.4 |
| | 3 | 1.8 | -1.1 | .6 | -1.8 | .6 | -1.3 |
| | 4 | -.3 | -2.5 | -2.9 | -3.1 | -.8 | -3.8 |
| | 5 | 4.1 | -5.6 | -1.5 | -2.3 | 6.6 | -8.9 |

TABLE V - Continued

| Case | Cycle | Pitch Up (deg) | Pitch Down (deg) | Pitch Cycle (deg) | Roll Up (deg) | Roll Down (deg) | Roll Cycle (deg) |
|---|---|---|---|---|---|---|---|
| 14 Average of 5 cycles | | 1.1 | -2.4 | -1.3 | -3.1 | -1.3 | -4.4 |
| 15 | 1 | -1.6 | 1.3 | -.2 | -5.0 | -.6 | -5.6 |
| | 2 | -2.0 | -1.2 | -3.2 | -6.0 | -3.8 | -9.8 |
| | 3 | -2.9 | -.2 | -3.1 | -8.8 | -.5 | -9.3 |
| | 4 | -1.5 | -.1 | -1.6 | -8.2 | 7.9 | -.3 |
| | 5 | .4 | -.2 | .2 | -8.3 | 4.0 | -4.3 |
| 15 Average of 5 cycles | | -1.5 | -.1 | -1.6 | -7.3 | 1.4 | -5.8 |
| 16 | 1 | -.9 | .3 | -.6 | .1 | -2.7 | -2.6 |
| | 2 | -.3 | .1 | -.1 | 1.8 | -1.8 | .1 |
| | 3 | .0 | -.3 | -.2 | 1.9 | -2.3 | -.4 |
| | 4 | .4 | .0 | .4 | 2.2 | -2.4 | -.3 |
| | 5 | -.3 | -.0 | -.3 | 2.5 | -2.4 | .1 |
| 16 Average of 5 cycles | | -.2 | .0 | -.2 | 1.7 | -2.3 | -.6 |

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13. ABSTRACT


~~Sikorsky Aircraft~~ has conceived an electrohydraulic feedback system that will provide position synchronization of four aircraft cargo hoists. To demonstrate the feasibility of the concept and to verify the method of analysis, ~~Sikorsky Aircraft~~ has designed, fabricated, and tested a model four-point synchronized hoist system. Test results show that the feedback system concept provides adequate synchronization control; i.e., the platform pitch and roll angles do not exceed ±5°. The analysis derived to predict performance of the feedback system was shown to be valid.


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| Feedback Control | | | | | | |
| Error Analysis | | | | | | |
| Hoisting Platform | | | | | | |
| Stability | | | | | | |

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